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TRANSLATION

CONTROL OF REACTION-THRUST MISSILES

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AIR FORCE SYSTEMS COMMAND

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UNEDITED ROUGH DRAFT TRANSLATION

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This book attempts to compile in most simplified and accessible form materials that have appeared in the foreign press on the subject of the principles of designing reaction-thrust missile control systems and methods of guiding them.

On the basis of data published in the foreign press we present a classification of all known guidance systems used in practice and in the process of development or production; there is a description of their operating principles and of the equipment and devices employed in the elements of the system. The tactical features of every system are examined, as are their advantages and shortcomings, including their effective range and accuracy. Some individual of the best known systems are described and the prospects of development in this branch of military technology are pointed out.

The book in intended for officers of the Soviet Army and Navy who are not specialists in this field of military technology. This book can also be useful for university students, students of military educational institutions and other individuals who may be interested in the problems presented in the book.

INTRODUCTION

Rapid development of automation, electronics and reaction-thrust engineering during the past decade has resulted in a new and powerful weapon for land and sea forces all over the world, namely the guided missile. Guided missiles were first used as early as World War II; however, since the end of the war a great deal of progress has been made in this field of military technology; a variety of types of guided missiles for many varied purposes have been developed. The guided missiles developed by other countries and introduced as defense equipment of their armies can be fired from points on the ground as well as from various carriers, such as ships, submarines, airplanes, etc., and aimed at the greatest variety of targets (on land, sea, in the air, or even under the water). Guided missiles are consistently becoming more universal (general purpose) weapons.

Guided reaction thrust missiles have an unusually wide effective operating range; they can be used over distances of several kilometers in the case of anti-tank missiles as well as for several thousand kilometers in the case of intercontinental missiles. The outstanding great advantage inherent in guided missiles over other types of weapons is their greater effectiveness in striking moving targets. This is extremely vital at present, since high speed means of attack have been introduced into the armament of armies and these are equipped to carry atomic and nuclear warheads.

The guided rocket missile is better suited to striking a predetermined target with greater accuracy because of the great quantity of varied equipment on board and outside, which makes up the so-called missile control system.

A guided rocket missile is a pilotless craft propelled by a reaction thrust engine and equipped with a special control mechanism, allowing the missile to be guided automatically toward a target or to move in space over a predetermined trajectory. Many countries have supplied their armies with guided bombs which are not equipped with jet engines and therefore do not belong in the same group with rocket missiles.

Guided missiles can serve a variety of purposes: combat use (for striking military targets), experimental use (for conducting aerial tests for the purpose of perfecting individual elements of the missile), use as guided moving targets (for firing practice), research use (for scientific exploration of the upper layers of the atmosphere), etc. Depending on their purpose, guided missiles exhibit various aerodynamic characteristics, designs, and control systems. This work is devoted to the study of problems connected with military guided missiles.

Depending on the launching site of the reaction-thrust missiles (including guided missiles) and the nature of the target, the missiles are subdivided into four categories: "ground-to-ground," "ground-to-air," "air-to-ground," and "air-to-air," which are, in turn, classified into subdivisions.

A missile's classification by subdivision is determined by the specific point of the launching site – whether on land, a ship, submarine, or airplane – and the target the missile is to strike (in the air, on land, a ship, or submarine).

The first classification "ground-to-ground" is subdivided: "ground-to-ground" as such, and "ground-to-ship," "ship-to-ground," "ship-to-ship," "ship-to-submarine," "submarine-to-ground," "submarine-to-submarine,"* The second classification includes subdividions: "ground-to-air," "ship-to-air"; the third classification: "air-to-ground," "air-to-ship," and "air-to-submarine"; the fourth classification has no subdivisions.

There is also a way of classifying guided missiles into four groups: ground (coastal), anti-aircraft, aviation, and ship, meaning: by ground — missiles of the "ground-to-ground" classification; by anti-aircraft — the subdivision "ground-to-air"; by aviation — various missile subdivisions fired from airplanes; and by ship — all possible classifications fired from aboard a ship.

Guided missiles of all the above classifications, depending on the presence of and the type of engine and aerodynamic or hydrodynamic systems used, are divided into airplane missiles, rockets (winged** and wingless), guided bombs and guided reaction-thrust torpedos. Wingless rockets are often referred to as ballistic rockets (missiles), which thus indicates the type of trajectory (ballistic curve) in which they travel. Guided reaction-thrust missiles in the airplane aerodynamic category are referred to as airplane missiles.

Various principles are employed in guiding a missile, and these depend on the tactical designation of the missile, flight conditions, and on the rated effective range. This work is devoted to the study of the principles of controlling guided missiles.

The control system is one of the most important parts of the armament complex which includes the missile which is being guided, and the effectiveness of guiding the missile toward its target de-

pends entirely on this system.

Guidance of missiles is accomplished by means of a complex system of automatic and remote automatic control and, consequently, it is a closed follow-up system which, since it is complex, can be represented as one consisting of many links or of many smaller follow-up systems (loops).

The complete structural diagram of the control system is composed of the following interconnected systems and links: the guidance system, the on-board control system, the body (frame) of the missile, the kinematic relationships between the missile and the target (kinematic element), and many other loops. In order to clarify the purpose and function of the various systems and links (Fig. 1) let us introduce several definitions.

The armament complex or the system of the guided missile is the aggregate of all installations necessary for determining and selecting a target, for launching and guiding the missiles, the missile itself, as well as its storage, assembly, and preparation for launching.

The missile guidance system (Fig. 2) is that part of the guided missile's armament complex which controls the launching installation and the missile in the process of preparation for firing, the actual firing, and the guidance of the missile to the target. Thus, the following are a part of the guidance system: means of determining the relative position of the missile carrier and the target, the equipment which calculates the necessary trajectory of the missile's flight for striking the target, and apparatus for the purpose of automatically guiding the missile in flight and which immediately provides for changes of its trajectory. The elements of the control system can be on the missile itself as well as on the

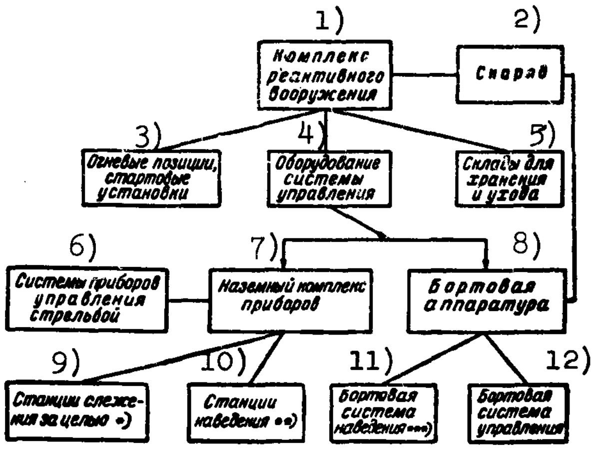

Fig. 1. Diagram of reaction thrust armament: *In guiding long-range missiles against ground targets there is no target tracking apparatus. **When independent guidance systems are used there are no ground guidance stations. ***In the case of independent guidance systems, the on-board guidance functions are accomplished by the program equipment. 1) Reaction thrust armament complex; 2) missile; 3) firing positions; launching sites; 4) control system equipment; 5) maintenance and storage warehouses; 6) firing control instrument system; 7) ground instrument complex; 8) on-board apparatus; 9) target tracking stations;* 10) guidance stations;** 11) on-board guidance system;*** 12) on-board guidance system.

object from which the launching and control or control alone takes place (from the ground, ship, airplane, or other guided missile). The loop of an extensive follow-up system which encompasses all the elements of the control system, is called the control system loop. The missile itself is also one of the elements of the control system, i.e., a link of this loop.

The firing control instrument system is the part of the system of missile control that handles the firing process of the reaction-thrust missiles (determining and selecting targets, input of target data, training of launching installations, and firing of the missile). For the majority of missiles this system differs very little from corresponding artillery systems (with the exception of the

missile firing process).

The guidance system is the part of the control system (equipment complex) which ensures the determination of the missile's position in space in relationship to the targets and the calculation of the required flight trajectory to be followed by the missile in order to strike the target.

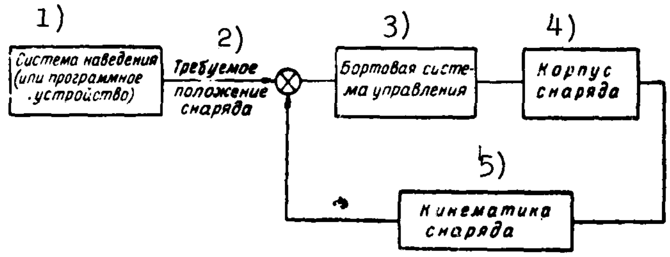

Fig. 2. Basic links of the complete control system loop. 1) Guidance system (or program equipment); 2) required position of missile; 3) on-board control system; 4) body (frame) of the missile; 5) kinematics of the missile.

The guidance system includes ground (ship, airplane) guidance stations, on-board guidance systems, computer equipment which can be installed either on board the missile or within the guidance station, and other apparatus. In some cases, there may be no guidance stations, and in that case the guidance system consists only of the on-board guidance loop.

The guidance system works out command signals regarding the missile's changes of trajectory which are then transmitted to the on-board control system, ensuring the missile's flight along the required trajectory.

The on-board control system (or the on-board control loop) is a part of the control system installed on the missile and serves the purpose of stabilizing the missile's flight or executing the change-of-trajectory commands issued by the guidance system.*

All missile control systems are divided into three basic groups

in accordance with their tactical capabilities: self-guidance (homing), remote-control, and autonomous systems. They differ in many respects; however, they differ primarily in their principle of operation and technical execution of their guidance systems.

The major part of this book is devoted to the description of the operational principles of presently known guidance systems. However, since it is impossible to examine the guidance system separately from the over-all control loop, the book presents a brief description of the installation, operating principle, and mutual interdependence on each other of all the other links of the control system: the body of the missile, its aerodynamics, on-board control system, and other elements of the guided missile which affect the selection of the type of guidance system for the known classifications of missiles.

[Footnotes]

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4	*In this case the word "ship" means a surface ship or a submarine on the surface, and "submarine" means a submerged submarine.
4	**Our literature often refers to airplane missiles as winged missiles.
7	*There is a close association between the ground and on-board guidance systems; however, each serves a different purpose. To explain better the difference between these systems the following comparison is sometimes used: the function of the ground guidance system is compared to the human brain, whereas the on-board system is compared to the muscles, coordination, orientation, and sense of balance of a human being.

Chapter I

BASIC ELEMENTS OF GUIDED MISSILES

Depending on their combat missions, guided missiles can be extremely varied in shape, dimensions, and assembly. Despite the variety of existing types and designs of guided missiles, they are characterized by many common design elements.

Every combat guided missile consists of the following basic elements: a body of definite aerodynamic design (frame), power plant including its mechanism and fuel sections, warhead and fuses, on-board control and guidance apparatus, control and stabilization instruments, and power supply. The above elements can vary in design, combat and technical characteristics, and they are selected for each type of missile on the basis of the missile's tactical mission. Every one of these elements uniquely affects the efficiency with which the combat mission is carried out, and all the elements together completely determine the tactical-technical characteristics of the guided missile. The location of the various elements within the body of the missile can also vary (Figs. 3, 4, and 5).

One of the most important parts of a guided missile is its control system, particularly the guidance system, on whose accuracy and reliability depends the utilization efficiency of guided missiles. Selection of a guidance system depends not only on the nature of target and the possible trajectories of its motion (in the case of a moving target), i.e., on the tactical designation

of the missile, but also on a number of other factors, including the characteristics of the various elements of the missile itself: the warhead, types of reaction-thrust engines (Vernier and booster), the shape and aerodynamic assembly of the missile, power sources, etc.

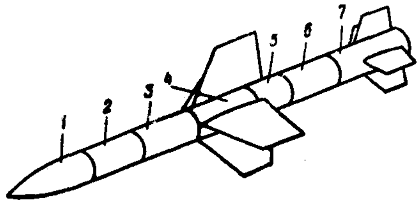

Fig. 3. Assembly diagram of "air-to-air" class guided missile. 1) Receiver; 2) computer; 3) power source; 4) automatic pilot; 5) fuse; 6) warhead; 7) engine.

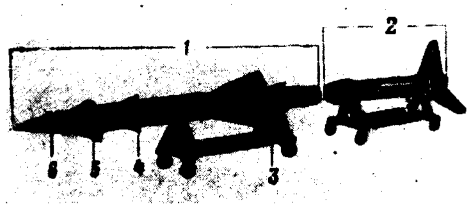

Fig. 4. Basic design elements of Nike anti-aircraft guided missile; 1) rocket; 2) booster; 3) stabilizers; 4) antenna; 5) control surfaces; 6) warhead.

The Warhead. Guided missiles can carry warheads for various purposes: armor-piercing, fragmentation, demolition, incendiary, cumulative, etc. The weight of the warhead is selected to be sufficient for incapacitating the target with one missile. In view of the fact that it is not always possible to strike a target that is moving at great speed, the warhead is usually supplied with a noncontact fuse. The fuse sets off the charge at the instant of flight close to the target. In the case of firing at targets on land that are immobile or are moving fairly slowly, the missile can be supplied with a noncontact fuse as well as a contact fuse which will go off on striking an obstacle.

In the case of total probability of a direct hit, the amount of explosives could be limited to an amount sufficient for the destruction of the target. However, since the probability of a direct hit is always less than 100%, the weight of explosives has to be

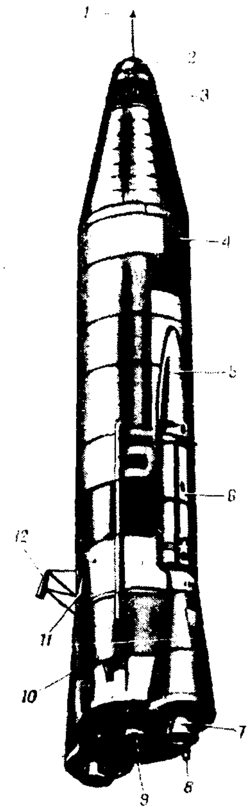

Fig. 5. Basic design elements of the American Atlas intercontinental ballistic missile. 1) Air pressure sensor; 2) anti-radar coated nosecone; 3) corrugated missile nosecone skin for reduction of electromagnetic wave reflection; 4) cylindrical thin-walled body made of a high-strength light-weight alloy; 5) missile control apparatus inside of side cowling; 6) middle sections of side cowlings containing guidance equipment (radio-and-inertial); 7) rotating combustion chambers of liquid rocket engines, subsequently to be dropped; 8) exhaust manifold of the turbopump assemblies of the engines; 9) sustainer engine with rotating combustion chamber; 10) missile tail fillet, dropped together with the booster engine; 11) inclined nozzles of the Vernier engines for the purpose of bringing the missile into trajectory and stabilizing it with respect to the longitudinal axis; 12) extended antenna.

increased in order to increase the area of possible target damage. Should the target be missed by a great distance, a rather great

amount of explosives would be necessary. Consequently, accuracy in aiming a guided missile should be achieved in order to eliminate errors exceeding the radius of warhead effectiveness. This is no easy task, since the speed of the missile's approach to the target can reach great proportions and, besides, the target can also maneuver.

The imperialist countries are of the opinion that guidance difficulties can be decreased by the development of small-dimension and light-weight atomic warheads that possess a greater destructive force. A similar decrease in weight and dimension of thermonuclear warheads which possess an even greater radius of effectiveness than the atomic, makes it possible to simplify the problems of developing engines (power plants) and control systems for intercontinental missiles.

However, in spite of the existence in the Soviet Union of thoroughly tested series-produced intercontinental rockets equipped with sufficiently accurate control systems, our government is in favor of the unconditional outlawing of this weapon of mass destruction.

Based on foreign press data, guided missiles, depending on their classification, can have a warhead of the following weight:

Anti-tank missiles	3-5 kg
"Air-to-air" classification	10-30 kg
"Ground-to-air" classification	20-100 kg
"Ground-to-ground classification, short range	300-700 kg
"Ground-to-ground" classification, intermediate and long range	1000 kg and over

Fuses. Noncontact fuses operate automatically whenever the missile passes at a predetermined distance from the target or is at a given altitude above the ground. In the case of anti-aircraft

guided missiles noncontact fuses are indispensable equipment.

Depending on the physical phenomenon which serves as the basis of the fuse's operation, noncontact fuses can be: radioengineering (radar), optical, magnetic, acoustic, etc. Radar and optical noncontact fuses are most frequently used in warheads on guided missiles.

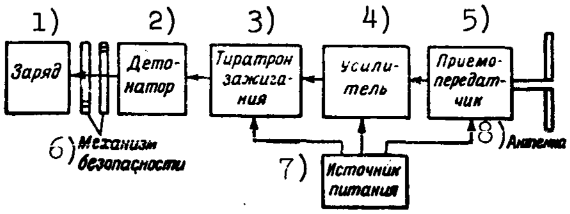

Fig. 6. Block diagram of radar fuse. 1) Charge; 2) detonator; 3) ignition thyratron; 4) booster; 5) transmit-receive unit; 6) safety mechanism; 7) power source; 8) antenna.

The best known radar fuse (or radio fuse) is a fuse which operates on the principle of using the Doppler effect.* This type of fuse (Fig. 6) includes: a radar transmit-receive unit equipped with a high-frequency continuous-oscillation oscillator, an antenna for sending out and receiving signals reflected by the target, an amplifier equipped with a thyratron and used as the terminal stage, an electric primer, and an auxiliary detonator for the explosion of the basic charge. In addition, the fuse must be equipped with automatic safety devices and a special automatic destruct device so that the missile can be destroyed should the target be missed or the control system malfunction.

After the missile has been launched, at a predetermined distance from the launching site, the radar fuse is armed (often by a command signal from the guidance station). The directional antenna of the fuse has a directivity pattern which assures the detonation of the missile in the vicinity of the target.

Whenever the target passes through the zone of effective transmitter activity part of the emitted energy is reflected from the target and is received by the receiving equipment of the fuse. Since a relative shift between the missile and the target takes place, the frequency of the signals received varies from the frequency of signals emitted. As a result of combining the reflected signal with the emitted signal, a voltage is created with a beat frequency equal to the difference between these frequencies. The beat frequency increases with the speed of approach. The resultant voltage is detected and transferred to the control circuit which detonates the explosion. The most advantageous instant for detonating the missile is obtained by combining the increase in signal amplitude and the instant at which the decrease in beat frequency begins to take place. The guidance signal is transferred to the thyratron grid which has so far remained closed, the thyratron opens, the plate current of the thyratron ignites the electric primer and, thus, detonation of the missile is achieved.

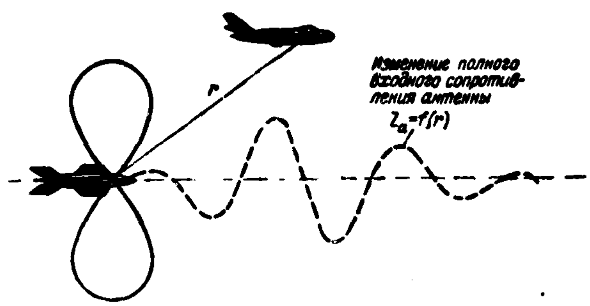

Fig. 7. Directivity pattern and nature of change in input inpedance of the radar fuse antenna. 1) Change in input impedance of antenna.

There are fuses that operate by another principle, i.e., changing the input impedance of the antenna upon receipt of the signals reflected from the moving target (Fig. 7). The beat frequency ob-

tained in the circuit as a result of load changes on the high-frequency oscillator is a function of the speed of the missile in relation to the target. This phenomenon is utilized for activating the fuse. The combination of the amplitude increase of the signal and the instant at which the decrease in beat frequency begins provides the opportunity for determining the most favorable instant for the detonation of the missile.

Whenever a guided missile or a bomb equipped with a radar fuse is used for striking a target on the ground, the fuse principle of operation remains the same; however, the reflected waves in this case do not emanate from a target in the air but from the surface of the earth. The electrical circuit of the radar fuse should be adjusted so as to produce the explosion at the altitude considered most effective for destroying the target.

Fuses operating in the above manner are not completely perfected. Therefore, we use radar fuses that are constructed on the basis of different principles as well.

Radar fuses can be active and semi-active, depending on the location of the source of the radio waves necessary for the shaping of the control signal.

Optical fuses operate on the principle of utilizing the heat or infrared rays emitted by the target. These optical fuses consist of a lens sensitive to infrared rays, a photocell, situated at the focal point of the lens, an amplifier circuit, and a pyro-cartridge (Fig. 8). Whenever a uniform surface is reflected in the photocell (for example, clouds), there is little change in the current of the photocell circuit, and the fuse is not activated. However, when the missile passes in the vicinity of the target, and the target falls within the field of view of the fuse, the intensity

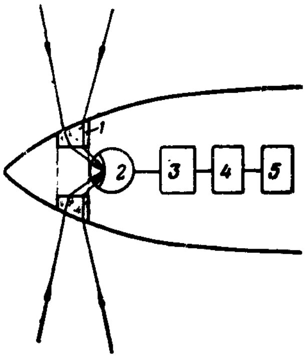

Fig. 8. Block diagram of optical fuse. 1) Toroid lens; 2) photoelectric cell; 3) amplifier; 4) thyratron; 5) detonator.

of the reflection onto the photocell changes abruptly, creating a photoelectric current pulse in the amplifier circuit, causing the activation of the cartridge and the detonation of the missile.

The amplifier power battery is not provided with an electrolyte in order to forestall the missile's detonation ahead of schedule. Only after the missile has been fired is the electrolyte injected into the battery through a pourous partition, under the influence of the acceleration that is developed.

Optical fuses can be employed in various missiles, regardless of the type of guidance system.

Reaction-thrust engines. Guided missiles are mostly equipped with reaction-thrust engines in order to create the thrust necessary for the flight of a guided craft. However, it should be noted that great velocities and distances are not always necessary for a guided missile: for example, anti-tank missiles powered by a reaction-thrust engine are not made for great distances or great flight speeds. Besides, not every guided craft needs an engine. For example, guided glider bombs are not equipped with engines.

Basically, guided missiles can be equipped with two types of engines: engines independent of environment (rocket) and those dependent on their environment (ramjet engines). The difference here lies in the fact that ramjet engines obtain the oxygen necessary for propellant combustion from the surrounding atmosphere and there-

fore cannot effectively operate at great altitudes in the rarefied layers of the atmosphere; however, reaction-thrust engines operate on a propellant containing the necessary supply of oxidizer, and, therefore, do not depend on altitude.

Reaction-thrust engines can, in turn, be divided into two classifications:

1) engines operating on the solid propellant which combines fuel and oxidizer; this classification includes powder rocket engines (PRD) [solid propellant reaction-thrust engines];

2) engines operating on liquid propellants (ZhRD) [liquid fuel rocket engines]; in this case fuel and oxidizer are usually stored in different tanks and are injected in a certain ratio into the combustion chamber.

A special feature of solid propellant engines is their ability to develop high thrust in a short period of time. Contemporary solid fuel rocket engines (PRD) can develop a thrust of scores of tons and their service life varies, depending on the designation of the engine.

Rocket engines operating on solid propellants are endowed with many substantial advantages regarding safety of operation, length of storage time, and convenience of operation. Heat-resistant materials used for the construction of the metal frames of the missiles operating on solid propellants make it possible to place the charge in the central section of the missile (in the wing section), as well as to expel hot gases through the nozzle by means of a heat-resistant exhaust tube.

Solid-propellant engines are effectively used as booster engines and auxiliary boosters.* Not every guided missile requires an auxiliary booster. A missile designed for prolonged flight and,

therefore, with enough time at its disposal to reach a normal flight speed with low initial acceleration (on the order of 2-3 g), does not require an auxiliary booster. A missile without a launching booster engine is usually (but not always) launched vertically, in order to simplify the problem of stabilization and control of missile flight during the period of acceleration when the control surfaces are not yet effective. During this period, one of the methods of deflecting the gas stream of the engine can be utilized for guiding the missile.

However, in most anti-aircraft, ballistic, and airplane guided missiles, launching boosters are used to reduce the launch time and the length of the launching rack to a minimum;

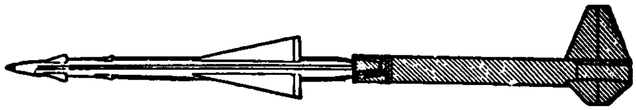

Fig. 9. American anti-aircraft guided missile Nike-Ajax equipped with a booster rocket (tandem booster).

these boosters assure, within a short period of time (from fractions of a second to tens of seconds), given high initial acceleration (approximately 30 to 50 g), missile acceleration up to the normal cruising speed or, at least, a speed great enough for the rocket or ramjet engine independently to increase the velocity to normal magnitudes, without impairing the combat mission.

At the present time, two designs of booster engines are used: a tail booster (tandem booster) and the booster bundle which is mounted directly on the body of the missile (booster pack). The former is widely used in the USA and the latter in England.

The design of the tandem booster (Fig. 9) has great advantages,

since the flight characteristics of the missile are not substantially impaired. However, it also has a series of inherent drawbacks: considerably greater length of missile assembly and extensive booster stabilizing surface, thus rendering storage and launching of the missile more difficult and the launching site more cumbersome. Control of the missile during the acceleration stage is more difficult and sometimes may require separate control systems located in the launching booster itself.

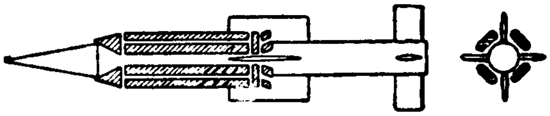

Fig. 10. English anti-aircraft guided missile Sea Slug, equipped with four booster bundles (booster pack).

The booster bundle (Fig. 10) consists of several independent solid propellant engines mounted around the body of the missile, between its wings. The compactness of this design is its advantage: the length of the missile is not increased, and large stabilizers for the booster engine are not necessary. The missile's center of gravity does not substantially differ in position for a missile with a booster engine or without; during the acceleration stage and after jettisoning of the booster engine the same control and stabilization system can be used. The drawbacks are a substantial increase in missile friction during the acceleration stage and the possibility of damage to the body of the missile at the time of booster-engine separation. Bundle jettisoning takes place as a result of the force of the aerodynamic resistance, or by means of ejection-cartridge explosions.

Liquid-fuel reaction-thrust engines are used on anti-aircraft, air, and ground rockets for medium and, particularly, long-range operations. Comparatively light liquid fuel rocket engines can develop considerable thrust. For example, in long-range rockets

it can reach over a hundred tons.

Ramjet (VRD) engines, whose thrust is developed on the basis of the velocity difference between the air entering the engine during flight and the stream of hot gases expelled from it, include the following types:

1) turbojets (TRD) employing additional air compression by means of a special installation consisting of a gas turbine and a compressor;

2) ramjet engines (PVRD) which employ preliminary air compression of the air entering the combustion chamber by means of the velocity head, under high-speed flight conditions (the so-called compressorless engines);

3) pulsejets (PuVRD) which do not employ continuous preliminary air compression, but fire intermittently.

A feature of the ramjet engine is its inability to develop thrust without motion; therefore, the missile cannot take off independently. Ramjet engine missiles are launched by means of booster engines or from an aircraft moving at a velocity of no less than 500 km/hr. Ramjet engines have found practical application for subsonic velocities; however, they reach maximum efficiency at a velolity corresponding to M = 4.5-5.0, when mass propellant flow rate is lower by a factor of approximately 6 in comparison to the propellant flow rate in a rocket engine of equal thrust. Ramjet engines are simple in construction, but their shortcoming lies in the fact that engine operation is a function of velocity, angle of attack, and altitude. Adaptation of ramjet engines to operating conditions at all altitudes is accomplished by the use of combined powerplants consisting of a ramjet engine and a ZhRD.

Turbojets are most economical with respect to fuel consumption

(flow rate). The following data can be used as a comparison: to produce 1 kg of thrust in a turbojet engine, an average flow rate of 1.1 kg/hr is necessary, whereas in the case of a rocket engine this flow rate amounts to 17 kg/hr. The turbojet's drawbacks are: large dimensions, weight, and frontal resistance.

Pulsejet engines of this class are usually used as flying targets because of their low flight speed.

The selection of engines for guided missiles is based on various considerations: required range, altitude, flight velocity, type of trajectory, etc.

Sources of power. In addition to the basic sources of power for sustainer and booster engines, a guided missile requires auxiliary sources of power for the operation of all equipment and instruments, such as the fuel system, control-surface drives, various types of electronic equipment, etc. Auxiliary sources of energy (power sources) should be independent of the basic power plant, as well as light in weight, reliable, and stable.

Auxiliary guided-missile power sources are usually divided into three categories: mechanical, electromechanical, and electrochemical.

Mechanical power sources consist of a prime mover (usually of the gas turbine variety) as well as fuel and oil pumps, etc. The working fluid for auxiliary turbogenerators is either a compressed gas (air, nitrogen, or some other inert gas), or some other chemical substance (cordite, hydrogen peroxide, or liquid fuels) which produces the gas needed to turn the turbine.

In addition, auxiliary mechanisms for fuel supply and control can be actuated by pressure accumulators, i.e., tanks containing compressed air (pressure accumulators), auxiliary liquid

(pressure accumulators) or powder reaction-thrust engines (powder pressure accumulators).

Electromechanical power sources are also equipped with a turbine prime mover; however, it actuates an electric generator rather than a pump.

An example of an electromechanical power source is the power plant for guided missiles, developed by the Garret Company, for actuating electric, hydraulic, or mechanical drives within the missile control system. In this installation the electric generator is mounted on the same shaft as the turbine whose wheel is rotated by the exhaust gases obtained as a result of the combustion of a solid or liquid propellant at a velocity of 2400 rpm. The generator's power amounts to 650 watts, but allegedly can reach 1600 watts. The entire unit weighs 11.5 kg, and its measurements are 330 x 250 x 180 mm.

Another example of an electromechanical power source is the unit installed on the anti-aircraft guided missile "Erlikon." It consists of a synchronous generator and a turbine, actuated by compressed nitrogen.

However, electromechanical power sources are not sufficiently reliable and rather complex in their operation. Consequently, work is being done on developing new, lighter, and more dependable power sources especially for guided missiles. For example, new chemical power sources have been widely used abroad – primary (power cell), as well as secondary (storage batteries). The most promising in this field are the silver (oxide)-zinc secondary and mercury primary cells.

Primary cells have the advantage over secondary storage batteries of being able to be stored in a discharged condition without

needing any care. The electrolyte can be stored separately and added at any predetermined time. Primary cells need not be charged and are more dependable than secondary storage batteries. However, secondary cells have other advantages that are important when they are used on guided missiles: rather high reliability, maximum power yield per unit weight and volume as compared to other sources, the ability to operate in a wide range of temperatures, a long storage time, endurance of vibrations and other mechanical disturbances, and simplicity of operation.

Silver (oxide)-zinc secondary cells are lighter by a factor of 6 and smaller by a factor of 5 in volume as compared to lead secondary cells of equivalent capacity: they can yield 130 watt-hours per 1 kg of weight, including the weight of the body and the grid. The basic drawback of silver (oxide)-zinc secondary batteries is their high cost, which exceeds the price of regular secondary cells by a factor of approximately 4.

According to foreign press reports, the American firm "Yardney Electric" manufactures silver (oxide)-zinc secondary batteries weighing 1.2 kg with measurements of 8.7 x 7.1 x 12.1 cm for the power supply of radio equipment on guided missiles. The battery has a capacity of 100 ampere-hours and a maximum discharge current of 2000 amperes. The batteries can operate at temperatures up to 125°C and can withstand impact pressures up to 1000 G's. The company also manufactures high-power batteries for the operation of servodrives with a capacity of 100 ampere-hours, a voltage of 28 v, and a discharge current of 300 amperes for a duration of 10 minutes; this unit weighs 38 kg and the high voltage 400 v batteries weigh 18 kg.

General Electric manufactures miniature solid electrolyte

batteries with a shelf life of 20 years. The battery's voltage is 25 v. The range of operating temperatures is from – 73° to + 274°C. Its dimensions are: 8.5 mm in diameter, 2.5 mm in length, and 4.72 grams in weight.

During the past several years, silver (oxide)-zinc secondary cells have been used particularly widely on guided missiles. They have been used on the Viking rockets and the Matador and Falcon missiles; they are also expected to be used on the Bomark missiles.

In addition to mechanical and chemical power sources on guided missiles, other sources can be used. At the present time, a great deal of work is being done in perfecting basically new power sources – solar and atomic batteries, etc.

The body design of guided missiles, which determines their aerodynamic design, will be examined in a separate (following) chapter in view of its particular importance to the control system.

[Footnotes]

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13	*The Doppler effect is generally the change in the frequency of oscillation received by the observer in the case of a shift between the oscillation source and the observer with respect to each other, said change being a function of the velocity and direction of their mutual shift. In the case of radar, the Doppler effect is different inasmuch as the receiver of electromagnetic oscillations reflected from whatever object is located in the vicinity of the transmitter of oscillations emitted toward the object. In this case the magnitude of frequency change, determined by comparing the emitted and received frequency, is a function of the radial velocity component of the shift of the radar and the moving object with respect to each other, and the sign of the frequency change is a function of the direction of this velocity vector (on approach, the frequency increases, on moving away, it decreases).

[Footnotes, continued]

Manuscript Page No.	
17	*Launching and auxiliary boosters are usually similar in design; however, their purpose is different; the launching boosters are necessary for normal starting conditions (attaining flight velocity) with reduced length of launching racks; auxiliary boosters (basically, in the case of anti-aircraft and aircraft guided missiles) are necessary for the fastest possible attainment of velocity.

Chapter II

AERODYNAMIC DESIGNS OF GUIDED MISSILES. THE EFFECT OF MISSILE SHAPE ON CONTROLLABILITY

In order to achieve a maximum of accuracy in guiding a missile toward a target, it is absolutely necessary to have good controllability, i.e., the missile should quickly and accurately assume the position in space which is commanded by the guidance system. The missile should also be easy to maneuver, in addition to being sufficiently stable. These requirements can be satisfied by both the on-board guidance system and by the appropriate design of the missile and its aerodynamic assembly.

The aerodynamic design of the missile is selected on the basis of its mission, flight conditions, and other tactical and technical requirements; all aerodynamic forces to which the missile will be subjected in flight are considered. At this point, let us study only winged guided missiles, since wingless ballistic missiles traverse the major part of their trajectory in accordance with the laws of external ballistics similar to artillery shells.

As a rule the airframe of a guided missile consists structurally of an oblong body (fuselage), the carrying surfaces [airfoils] (wings), control surfaces, and stabilizing surfaces (stabilizers). The control and stabilizing surfaces of a missile are usually referred to as the empennage of the missile.

We differentiate among several aerodynamic designs of missiles

depending on the number of carrying and control surfaces.

Should a missile be equipped with four mutually perpendicular wings as well as four mutually perpendicular tail surfaces, the design is referred to as a cross-shaped guided missile design. There are two variations in this design:

1) tail surfaces situated in the same plane as the wings (Fig. 11a);

2) tail surfaces situated in planes forming a 45° angle to the wing surfaces (Fig. 11b).

a) b)

Fig. 11. Cross-shaped assembly diagrams of guided missiles — wings and control surfaces are: a) in the same plane; b) at an angle of 45° to each other.

The difference between these two versions of cross-shaped design is not very great from the point of view of aerodynamic effect, and is of no great significance with respect to the control of the missile.

The selection of empennage position is primarily based on other considerations: ease of attaching launching and acceleration boosters, dimensions of the launching installation, and convenience of operation.

If a missile equipped with two wings and two systems of control surfaces which function in a way similar to ailerons and elevators on an airplane, the assembly is referred to as an airplane assembly (Fig. 12).

The difference between the cross-shaped and airplane guided-missile assemblies lies in the fact that the former achieves missile

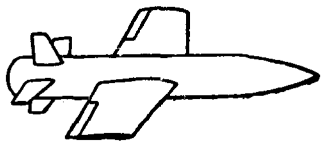

Fig. 12. Airplane assembly diagram of a guided missile.

control independently in two mutually perpendicular planes — individual control surfaces for each plane, whereas the latter requires the missile to execute a simultaneous and coordinated turn about the longitudinal axis (banking) in order to turn, and consequently the flight direction must be changed (the typical airplane turning maneuver).

A missile can be guided both by means of control surfaces as well as by means of wings, which are mobile (turning) in such cases.

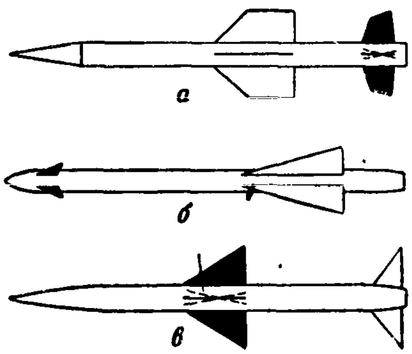

Fig. 13. Aerodynamic diagrams of guided missiles. a) Guidance empennage; b) Canard configuration; c) controlled wing.

Depending on the surfaces by means of which missile control is accomplished and depending on where they are located on the missile, there can be three versions of aerodynamic guided missile designs: controlled empennage (Fig. 13a), controlled wing (Fig. 13c), and Canard configuration (Fig. 13b).

In the "controlled empennage" design, the control surfaces are located in the tail section of the missile and the wings, which act as carrying surfaces, are located in the middle section of the missile.

In the "controlled wing" design, the wings serve as control surfaces, which simultaneously are the carrying surfaces, thus employing the tail surfaces as stabilizers.

In the "Canard configuration" design, small control surfaces are located at the front end of the missile and large carrying surfaces (wings) are located closer to the tail end of the missile.

All three versions of aerodynamic design can be employed in the cross-shaped and airplane guided-missile assemblies. Every one of the above has its advantages and disadvantages from the viewpoint of aerodynamic properties. In order adequately to analyze and evaluate these designs it is necessary first to acquaint ourselves briefly with basic aerodynamic concepts as they apply to guided missiles.

The missile's position in space can be determined by the three coordinates (x, y, z) of its center of gravity within the earth's system of coordinates (Fig. 14), adopting the launching site as the origin of this system. The X axis is horizontal (usually in the direction of firing), the Y axis is vertical, and the Z axis is perpendicular to the first two axes.

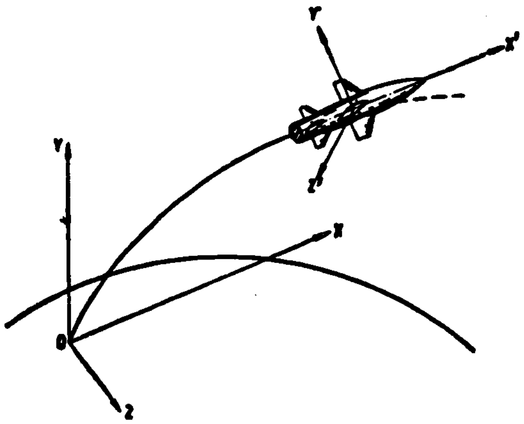

Fig. 14. Position in space of earth and connected coordinate systems.

The orientation of the missile in space is characterized by the mutual position of the moving coordinate system (x', y', z') connected with the missile and the earth's fixed coordinate system. The origin of the missile coordinate system is located in the center of gravity of the missile, and the X' axis is located along the longitudinal axis of the missile, the Y' axis and the Z' axis are

located perpendicularly to the longitudinal axis in the vertical and horizontal planes of symmetry of the missile, respectively.

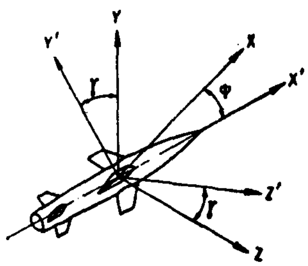

Fig. 15. Angles of yaw ψ and roll γ.

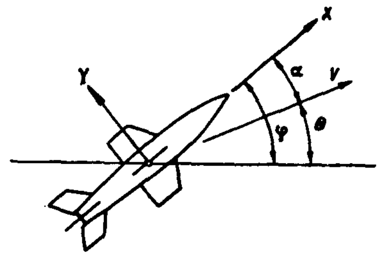

Fig. 16. Vertical plane angles: φ) pitching angle; α) angle of attack; θ) trajectory slope angle.

The relative position of the axes of the two coordinate systems and, consequently, the position of the missile in space is fully determined by three angles (Figs. 15 and 16): the angle of pitch φ (the slope angle of the longitudinal axis X' of the missile relative to the horizon plane XZ), the angle of yaw ψ (the deviation angle of the longitudinal axis X' of the missile relative to the vertical plane XY), and the angle of roll γ (the slope angle of the longitudinal axis Y' of the missile relative to the same vertical plane XY).

A moving missile describes a certain trajectory in space. Generally, in the case of missile flight along a trajectory the velocity vector V, characterizing the direction of flight, does not coincide with the longitudinal axis X' of the missile and is directed along the tangent to the trajectory. Consequently, the position of the missile in the vertical plane can be additionally characterized by two more angles: the angle of attack α (the angle between the longitudinal axis X' and the velocity vector V) and the slope angle of the trajectory θ (the angle between the velocity vector V of the missile and the horizontal plane XZ). Consequently,

the angle of pitch φ can be expressed

$$\varphi = \alpha + \theta$$

The angle of attack is formed by means of the control units of the missile. The actual values of the angle of attack are usually relatively small (not exceeding 6-10°). In cases in which the flight direction of the missile coincides with its longitudinal axis, the angle of attack equals zero, and the slope angle of the trajectory equals the angle of pitch.

The missile's position in the horizontal plane is, in addition, characterized by the slip angle β (the angle between the longitudinal axis of the missile and the velocity vector in the horizontal plane).

In addition to the thrust P (effective only in the active sector of flight) and the force of gravity G of the missile, the missile in flight is affected by various aerodynamic forces whose magnitude depends on the altitude and velocity of flight, the aerodynamic design of the missile, and the location of the control units. These forces (Fig. 17) are: the frontal resistance of the air against the body of the missile and its empennage, and the lift created by the airstream along the carrying and control surfaces of the missile. The lift in the vertical plane is what is actually referred to as lift.

A frontal resistance force is always present during a missile's flight through the atmosphere, regardless of angle of attack, and is a weak function of this angle. The lift is directly proportional to the angle of attack (slip angle) and will be reduced to a minimum in cases in which the missile's direction coincides with the direction of the longitudinal axis of the missile, i.e., when α and β are equal to zero.

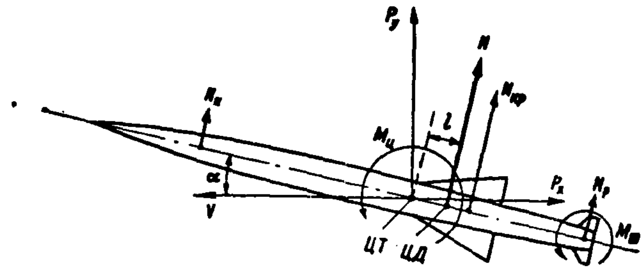

Fig. 17. Aerodynamic forces and moments acting on the missile: N_k, N_{kr}, N_r) Normal components of aerodynamic forces (of the airframe, the wings, and the control surfaces, respectively); N) resulting normal force; P_x) frontal resistance force; P_y) lift; M_{ts}) total moment of the missile; M_{sh}) hinge moment of the control surfaces. (V is the velocity vector; α is the angle of attack; l is the stability arm).

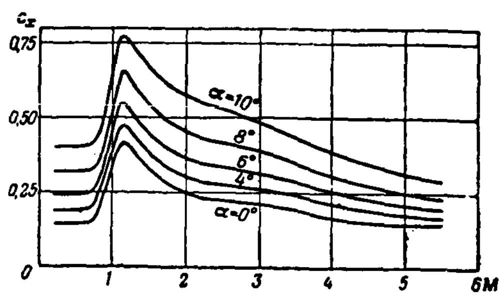

Fig. 18. Frontal resistance coefficient c_x of the ballistic missile as a function of Mach number and the angle of attack α.

The mathematical expressions point out the factors on which the magnitudes of these forces depend.

Frontal resistance P_x is determined by the following formula:

$$P_x = c_x \frac{\rho V^2}{2} S_x,$$

where ρ is the air density; V is the flight velocity of the missile (in an undisturbed atmosphere); S_x is the characteristic area (maximum cross section); C_x is the frontal resistance coefficient.

The lift P_y of the missile is expressed as follows:

$$P_y = c_y \frac{\rho V^2}{2} S_y,$$

where S_y is the characteristic area (wing area); c_y is the coefficient of lift.

The dimensionless coefficients c_x and c_y (Figs. 18 and 19) are usually determined in wind-tunnel tests. Basically, these depend on

the shape of the missile and the flight velocity, and somewhat less on other factors (air density and the linear dimensions of the various parts of the missile).

The over-all system of aerodynamic forces distributed along the missile's surface can be expressed in terms of the resultant of these forces, the so-called total aerodynamic force. Whenever this force is applied to the missile's center of gravity, provided that the angle of attack is not equal to zero, a moment will thus result which will turn the missile into the pitch plane. This moment is referred to as the stabilizing moment M_{st} of the missile (or the pitching moment); its value is determined by the formula

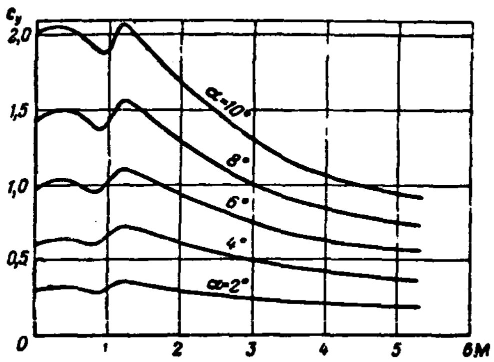

Fig. 19. Lift coefficient c_y of ballistic missile as a function of the Mach number and angle of attack α.

$$M_{ст} = c_m \frac{\rho V^2}{2} S_y l_x,$$

where $\underline{l}_x$ is the characteristic linear dimension (wing cord or length of missile); c_m is the moment coefficient (approximately of the same nature as c_x and c_y).

The resultant of the aerodynamic forces can be applied to any other point along the longitudinal axis of the missile, in relationship to which point the resultant moment will vanish. This point is referred to as the center of pressure and is located along the longitudinal axis of the missile, usually somewhat aft of the center of gravity. This distance between the center of gravity and the center of pressure is determined by the degree of stabilization or stability of the missile and is called the stability arm (Fig. 20).

Whenever the stability arm has a positive value (the center of pressure is located aft of the center of gravity), the dynamic forces will produce a moment that tends to decrease the angle of attack and restore the original direction of the longitudinal axis. In this case the missile will be statically stable. Whenever the center of pressure is located ahead of the center of gravity (which can happen in the case of missiles without control surfaces) the missile will be statically unstable. In order to obtain stability it is necessary to move the center of pressure farther back, and this is accomplished by means of control surfaces (stabilizers). In this case the relationship of the stability arm to the length of the missile is called the stability coefficient (margin).

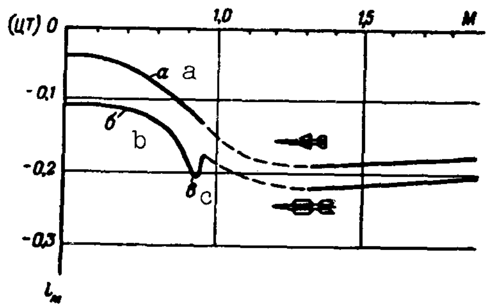

Fig. 20. The stability arm $\underline{l}$ of an anti-aircraft missile as a function of flight velocity with varying wing shapes. a) Delta wings; b) trapezoidal wings; c) sudden shifting of the center of pressure with approach to M = 1.

In addition to the basic forces and moments that have been examined, we should consider the damping moment which is the sum of individual local aerodynamic moments produced along the surface of the missile as a result of changes in the flow-past conditions due to turns and oscillations of the missile. The damping moment is opposite in direction to missile rotation, and its magnitude is proportional to the angular velocity ω of the missile.

The damping moment M_d in the pitch plane is determined by the following expression:

$$M_x = c_x \frac{\rho V^2}{2} \frac{\omega}{V} S_y l_x^2,$$

where ω is the angular velocity of missile rotation; $\underline{l}_x$ is the characteristic dimension (length of missile); c_d is the damping

moment coefficient.

Usually, the damping moment of a typical missile is smaller than the stabilizing moment by a factor of approximately 10.

The stabilizing and damping moments form the total moment M_{ts} of the missile.

All the forces and moments studied above pertain to one plane — the pitch plane.

With respect to forces and moments acting on other planes, the lateral force and rolling moment should be mentioned.

The lateral force P_z produced on deflection of the rudder (direction), is analogous in nature to the mathematical expression for lift; however, this force acts on the horizontal plane alone and produces the slip angle β.

The rolling moment is of interest for the study of some aerodynamic effects on the motion of the missile in the pitch plane. The roll moment M_l acting on the missile's longitudinal axis is expressed as follows:

$$M_l = c_l \frac{\rho V^2}{2} S_y l_z,$$

where l_z is the characteristic linear dimension of the transverse plane (wingspan); c_l is the roll moment coefficient.

The roll moment coefficient c_l changes in proportion to the aileron-deflection angle and the angular velocity of roll.

Some of the aerodynamic forces acting on the control units (surfaces) can be brought to the point of application, i.e., the control surface hinge. These forces produce the control moment or the hinge moment M_{sh}.

As can be seen from the above formulas, the magnitude and effectiveness of the forces studied depend on the external flight

conditions, aerodynamic assembly of the missile, and flight velocity. Summing the forces applied to the missile, and projecting them onto the corresponding axes, as well as summing all the moments with respect to the center of gravity, a system of equations of motion for the missile in one plane can be obtained. Whenever a missile executes a complicated motion in space (as, for example, an anti-aircraft missile with respect to a maneuvering target), it is necessary to study the forces and moments in terms of three coordinate axes and introduce additional coordinates which would completely determine the position of the missile. The number of equations in this case will increase.

For a complete mathematical characteristic of guided-missile flight, in addition to the equations of motion, equations of control must be derived, and these will express the control forces (or deflection angles of the control surfaces) as functions of various parameters of motion or time. The form and number of these equations will depend on the control system and the missile guidance methods which are selected.

In the case of certain types of guided missiles, intended for striking immobile and slowly moving targets, the maximum magnitude of lift for the missile is of secondary importance; however, in case the missile is intended for striking a fast moving target such as, for example, jet interceptors, this factor becomes extremely important, since on it depends the ability to execute the necessary maneuver. To produce the required lift, corresponding lifting surfaces are called for. The greater the wing area, the greater the lift (or lateral force), given the same speed and identical angles of attack. Greater lift can swiftly change the direction of missile motion. In the case of missiles operating at various altitudes,

maneuverability and controllability should be calculated so as to provide adequate airfoils and appropriate control-unit efficiency for high altitudes, whereas, for low altitudes sufficient airfoil strength to permit flight under the stress of maximum G forces.

We know that a missile having a definite wing area at a given altitude can follow a trajectory whose curvature will not exceed some maximum magnitude. This maximum trajectory curvature is obtained with the maximum normal G force (lateral acceleration). Should the calculations be incorrect, it can happen that at high altitudes the control surface of the missile will be deflected through the maximum angle, and the maximum magnitude of the control force thus produced will be inadequate to turn the missile with the required (theoretical) curvature of trajectory.

The magnitude of the forces acting on the missile (and its various parts), depends on the conditions of air flow about the missile at various flight velocities. The shape of the individual parts of the missile is selected on this basis and should be streamlined for rated flight velocities.

The body of any guided missile is usually well streamlined and has a pointed nosecone. The middle part of the missile is generally cylindrical in shape, and the tail section is a truncated cone. To reduce head resistance, the smallest possible body diameter is selected, provided all the equipment and instruments can be distributed within it.

The force of the frontal (head) resistance consists of two components at any flight velocity: friction and pressure. In cases of small flight velocities, friction is the principal factor in frontal resistance. On the other hand, under high flight-velocity conditions, the dominant factor is pressure, which can be divided

into two components: pressure at the front and expansion in the rear. From the viewpoint of head-resistance magnitude, the great nosecone pressure is of considerably greater importance than the small vacuum created at the flat tail base.

In the case of supersonic velocities the force of the frontal resistance increases greatly because of the wave resistance produced by compression waves (high pressure zones or, in other words, shock waves).* To decrease the nosecone pressure, a suitable shape is usually selected (for example, ogival), disregarding the expansion in the tail section. Therefore, in cases of high sonic velocities it is quite permissible to employ a blunt tail-section shape for the missile.

In cases of subsonic and supersonic velocities of missile flight with an angle of attack, the airflow conditions change because of the lateral air movement. This airflow leads to the additional formation of vortices and, consequently, to additional resistance, so-called induced resistance.

The pronounced difference in airflow conditions about the body and flat surfaces at subsonic and supersonic velocities has a great effect on the design of the missile and its surfaces.

Shapes of guided-missile wings can be extremely varied. As we have pointed out, the area of the wing is determined by the magnitude of the control (lift and lateral) force necessary to ensure missile maneuverability as provided by the guidance method. The size of this surface depends on the altitude and flight velocity of the missile: as the altitude increases, the size of the required wing area increases also; as the velocity increases, wing area decreases.

The wing shape, in plan, is selected so as to ensure stability and controllability of the missile in flight, over the entire

range of changes in flight velocity and minimum frontal resistance. Rectilinear, trapezoidal, and delta wings (Fig. 21), generally of small span, are used on guided missiles. Delta and trapezoidal wings, generally made to have swept-back leading and nonswept-back trailing edges, are the most common. Great sweepback reduces wave resistance, but a swept-back trailing edge is not mandatory, since at supersonic velocities it affects the region behind the edge rather than wing frontal resistance. Moreover, a nonswept-back trailing edge is much more convenient for the positioning of control units.

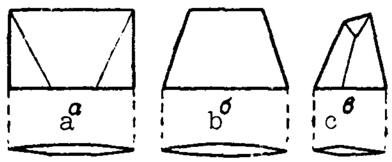

Fig. 21. Typical guided-missile wing shapes
a) rectangular, with rhombic shape, and flat sections; b) trapezoid with double-convex shape; c) trapezoid, with rhombic shape.

For missile flights at supersonic velocities, thin pointed surface shapes are the most advantageous.

Guided-missile control units are quite different from those of airplane*missiles and they may exhibit great variety. A change in control-unit position results in the appearance of an angle of attack which in turn produces lift and the corresponding normal missile acceleration in the direction assigned by the control system. In missile flight in airless space, missile control is achieved by the stream of exhaust gases acting on the gas vanes or directly by the turning of the engine combustion chamber (Fig. 22).

Control surfaces such as flaps on stabilizers, "empennage" surfaces, and the wings themselves, may be postioned on any part of the missile, depending on the aerodynamic design of the missile.

If the "empennage" surfaces are situated at the front of the missile (they may either be controlled or uncontrolled), and they

usually do not produce stabilization, but actually destabilize. Therefore, fixed front-end "empennage" surfaces are usually referred to as destabilizers. However, destabilization is not always a negative factor. In certain cases, some degree of destabilization is useful, i.e., whenever it is necessary to increase missile maneuverability.

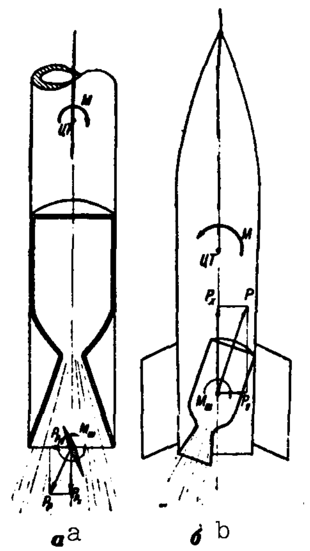

Fig. 22. Ballistic rocket control (surfaces). a) Gas vanes; b) rotating engine.

Controlled front-end surfaces are called nose vanes. They have the advantage of making it possible to control a two-stage missile in flight both with a booster and after the booster has been jettisoned.

Control surfaces located at the tail serve the combined function of elevators and rudders, as well as acting as ailerons. The ailerons located along the trailing edge of the "empennage" surface or the wing cantilever beams control the missile and serve to stabilize roll.

Tail control surfaces can be mounted both with fixed surfaces (stabilizers) as well as in the form of individual (independent) hinged control surfaces. The former are usually used on missiles of subsonic velocities, and the latter on missiles of sonic and supersonic velocities.

The control surfaces of supersonic missiles, as well as the lifting surfaces, are usually small, thin, and usually have sharp edges. Nevertheless, these are capable of producing considerable stresses, allowing the missile to maneuver with normal G forces

ranging from 7 to 20 g, produced by great dynamic (ram) pressure. With the deflection of such control units, aerodynamic forces arise at the most deflected control surfaces. Deflected control surfaces cannot change the lift or lateral force produced on the fixed wing and "empennage" surfaces located in front of the control surfaces as is the case under subsonic velocity conditions. This is explained by the fact that under supersonic velocity conditions, the action of aerodynamic forces (sound waves) cannot be propagated in the direction of flight. Thus, under supersonic velocity conditions, the basic advantages of conventional flap-type control surfaces are lost. Hence the necessity of replacing the conventional control surfaces by hinged "empennage" surfaces or wings, or to locate control surfaces ahead of the wings.

The selection of an aerodynamic design for a missile should be based on a consideration of the possible interference of airflows around the body and wings, given an angle of attack not equal to zero. An inclined missile body directs the flow of air along its body at an angle to the wing. The airstream from the body, on striking the wing, increases its angle of attack which, in the area adjacent to the body of the missile, is virtually doubled. However, for supersonic flight velocity, it is advantageous to have a small angle of attack. Therefore, measures are taken to eliminate harmful airstream interference around the body and the wings of the missile.

To ensure the stability of nonrotating guided missiles as well as airplanes, stabilizing surfaces are necessary. Stability problems are extremely complicated for a missile, since the center of wing pressure changes with any change in the angle of attack as well as with changes in velocity (Mach number). In addition, airstreams from the wings, located in front of the stabilizing surfaces, can

interfere with the streams flowing over the stabilizers located in the tail section. To minimize interference, the stabilizing surfaces are very often mounted in planes sloping at a 45° angle to the surface of the wings.

Whenever a missile is stabilized in flight by means of its tail "empennage" surfaces it exhibits some tendency to rotate about its own axis, since it is impossible in practice to make a missile exactly symmetrical. It is difficult to make the stabilizers exactly parallel, and even if it could be done, the missile would still rotate because of the unevenness of its surface. Rotation is often intolerable, since it can interfere with the operation of some instruments installed within the missile; in that case, special anti-rotation equipment is necessary. It is sometimes felt that some rotation is desirable, since it equalizes the effects of the missile's lack of symmetry, and this in the end can decrease missile scattering.

Let us briefly examine the features of known aerodynamic designs, as well as their basic advantages and disadvantages from the point of view of missile control.

The controlled "empennage" surface design employs the control surfaces installed in the tail section of the missile to increase the angle of attack of the entire missile body, and the wings are used to obtain the necessary lift. The advantage of this design lies in the fact that the control surfaces are usually of small dimensions. The characteristic feature of this design lies in the fact that the angle of attack is somewhat delayed with respect to the turning of the control surfaces, as a result of which lift is obtained only after the entire missile angle-of-attack has been established. From the standpoint of maneuverability and controlla-

ility this is a drawback of the design.

The controlled design has the advantage that the lift necessary for maneuvering is produced immediately, as soon as the wings begin to turn. However, this advantage cannot always be put to use, since the turning wings have a considerably larger lifting surface as compared to the tail control surfaces, and consequently, a much greater hinge moment; this results in a considerable delay in servomechanism execution of commands as compared to the case involving tail control surfaces. This requires greater power and dimensions for the servomechanism. In addition, the clearance between the cantilever-beam of the wing and the fuselage produces a loss of the lift created by the root section of the wing, and this represents a major part of the total lift. In this case, the tail control surfaces ensure the necessary stability. The turning wing thus becomes structurally heavy; however, it makes possible a convenient interior assembly of the missile whenever the control apparatus and the automatic pilot are located in the middle section of the missile, directly in the vicinity of the control units (wings). A positive feature of this design is the possibility of gaining altitude without increasing the angle of attack of the entire body of the missile.

The canard configuration features small control surfaces located in the nose section of the missile, and these are used to increase the angle of attack of the entire body, and the large wing surface in the tail section is used to achieve the required maneuverability. The apparent advantage of this design lies in the fact that the front control surfaces produce lift that acts in the same direction as the total lift of the missile. This results in a rapid creation of the lateral (normal) acceleration necessary

for maneuvering. The British are of the opinion, however, that in reality the harmful effects of the airstream from the front control surfaces to the basic wings of the missile are so great that they completely offset the above advantage of the design, to the point of being more serious. The small control surfaces and the ability to gain altitude rapidly are still advantages of the design.

In order to gain a better understanding of the control of missiles of various aerodynamic designs it is expedient to examine missile control methods employed in cross-shaped and airplane-type missile assemblies.

A guided missile of any cross-shape design almost always exhibits rigorous roll stabilization, so that in maneuvering in any plane the effects of roll are eliminated and control of the missile in the two mutually perpendicular planes (vertical and horizontal) is accomplished independently: one pair of control surfaces controls heading, and the other controls pitch. A maneuver in any inclined plane is accomplished by communicating simultaneously to the missile an angle of attack in two planes, each angle independent of the other. In the case of small angles of attack (below 10°) such control is accomplished without particular difficulties. However, in the case of large angles of attack, we encounter the mutual effect of motion in two planes. This is a result of the "overlapping" of the airstreams on some parts of the lifting and control surfaces, with the simultaneous deflection of the missile by the angle of attack in the pitch plane and by the slip angle in the yaw plane; this results in unequal lift for the surface pairs and brings about disturbing moments of roll. This can lead to instability of motion, particularly in the case of missiles with various longitudinal and lateral characteristics. In practice, how-

ever, simultaneous maneuvers with great angles of attack in both planes occur but rarely over great periods of time.

The method for controlling a missile of cross-shaped design is referred to as rectangular-coordinate-system control.

An airplane-type guided missile is not stabilized with respect to roll, since a coordinated turn is employed for the execution of the maneuver in this case, and this in turn requires simultaneous roll to a certain position of the lifting surfaces and the communication of the necessary angle of attack. In this case the system of control surfaces is so arranged that one pair of surfaces, acting as ailerons, turns the missile about its longitudinal axis, and the other pair, similar to elevators, changes the flight direction of the missile. The angle of roll during the maneuver is determined by the radius of the turn and flight velocity; however, it is always less than 90°. A design with two turning wings, acting independently of each other, and four fixed tail stabilizers is considered preferable.

The control method for the airplane-type missile is referred to as the polar coordinate control system. The accuracy of this method depends greatly on the accuracy of roll execution and the speed of it's change. In the case of roll that does not correspond to turn, a pitch disturbance is produced, and this requires the introduction of correction factors which are executed in the control system by means of the couplings between the control channels (the so-called cross couplings). Airplane-type designs are mostly used for missiles of the "ground-to-ground" classification in which altitude control is accomplished by an altimeter, and heading control requires only insignificant additional turns.

On the basis of foreign data, a comparison of cross-shape and

airplane-type missile designs shows that from the point of view of control accuracy there is a very insignificant difference between them. The airplane design has some structural advantages, i.e., given the same lift, a smaller over-all wing area is required, and this decreases the weight of the missile and simplifies the launching installation.

There is one more method of control, the so-called interception method (a variation of the polar coordinate control system). This method involves the following: the trailing edges of the wings or stabilizers have thin control surfaces installed perpendicularly to the air stream (stream breakers or interceptors), which are made to vibrate continuously at a frequency of 10-20 cps by means of an electromagnetic drive. The principle of control involves changing the duration of surface deflection in each maximum deflection position. Whenever no maneuvers are being executed, the stream breakers vibrate uniformly, remaining in their extreme positions for equal periods. Whenever a maneuver is to be carried out, the stream breakers are kept in one extreme position for a longer time and, correspondingly, less in another. Should it be necessary, the stream breakers can be kept in any extreme position. An advantage of this method of control is the low inertia (lag) of the servomechanisms and, consequently, a faster reaction to control signals. In addition, the interceptor system weighs less and is more compact in comparison to the usual servo-control system. A drawback of the interceptor method is the substantial increase in missile head resistance and inefficiency under conditions of high flight velocity.

After the aerodynamic design of the missile has been selected and its design computed, i.e., when we have an adequate idea of missile flight stability and controllability, subsequently, in

planning of the on-board control system we take into consideration the possibility of short-term or constant factors which might disturb the missile, affecting the accuracy of missile guidance to the target. The random or short-term factors include the various types of disturbances brought about by changes in external flight conditions or by the uneven performance of the engine, i.e., wind gusts, unforeseen changes in engine thrust, etc. The systematic or constant factors include certain technological imperfections or errors in the design of the missile, such as inaccuracies in the manufacture of the missile body, the wings, stabilizers, or the installation of the engine slightly off center.

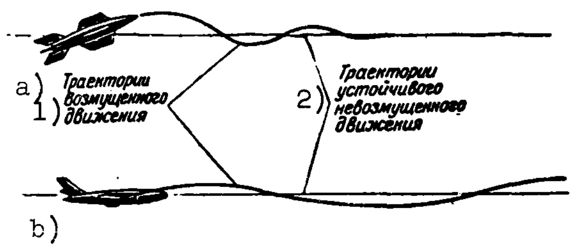

Fig. 23. Angular oscillations of guided missiles on trajectory; a) short-period oscillations (rocket); b) phugoid (airplane-missile); 1) trajectory of disturbed motion; 2) trajectory of stable undisturbed motion.

Without the influence of these factors on the missile, and if we take into consideration only the influence of the above-mentioned natural forces, the missile would carry out an assigned so-called undisturbed motion. However, this never happens in practice.

Under the influence of constant factors, basically due to changes in velocity, long-period or so-called phugoid oscillations are produced (Fig. 23).

In some types of missiles, phugoid oscillations are so slight that they are not taken into consideration.

Under the influence of short-term disturbances, as well as in carrying out a turn (changing the angle of attack), the missile deviates somewhat from the trajectory of undisturbed motion; however, given a positive stability margin, it will return to its original position, passing through this position (because of inertia) through some angle to the opposite side. Thus, angular oscillations will be produced for some time, but these will, however, be attenuated as a result of the damping moments. The period of these oscillations is usually small (it basically depends on the stability coefficient), and as a result such missile oscillations are referred to as short-period oscillations.

Thus, it is apparent that in reality the flight of a guided missile does not take place along an exact theoretical trajectory, but that certain deviations exist, and only sometimes does the missile approach the assigned line of motion. This has its effect on the accuracy of missile guidance to the target.

Consequently, the on-board control system must achieve maximum missile flight stability, i.e., to limit all oscillations and cause them rapidly to decrease, in addition to carrying out the guidance system commands, since it is impossible completely to eliminate these oscillations; these tasks are in addition to the elimination of the constant factors that had not been predicted in advance.

[Footnotes]

Manuscript Page No.	
37	The phenomenon of the appearance of the first compression waves, beginning at the critical subsonic velocities, is

[Footnotes (cont'd)]

Manu-script Page No.	
37 (cont'd)	referred to as the wave crisis.
38	Excluding certain airplane missiles in which the control units are similar to those of an airplane.

[Transliterated symbols]

Manu-script Page No.	
31	$N_{к} = N_{k} = N_{korpus} = N_{airframe}$
31	$N_{кр} = N_{kr} = N_{krylo} = N_{wing}$
31	$N_{р} = N_{r} = N_{rul'} = N_{control\ surface}$
31	$M_{ц} = M_{ts} = M_{tselyy} = M_{summary}$
31	$M_{ш} = M_{sh} = M_{sharnirnyy} = M_{hinge}$
31	ЦТ = TsT = Tsentr tyazhesti = Center of Gravity
31	ЦД = TsD = Tsentr davleniya = Center of Pressure
32	$M_{ст} = M_{st} = M_{stabiliziruyushchiy} = M_{stabilizing}$
33	$M_{д} = M_{d} = M_{dempfiruyushchiy} = M_{damping}$

Chapter III

ON-BOARD MISSILE CONTROL SYSTEM

The on-board missile control system (or in other words, the on-board loop) represents a link in the over-all control-system loop (Fig. 24).

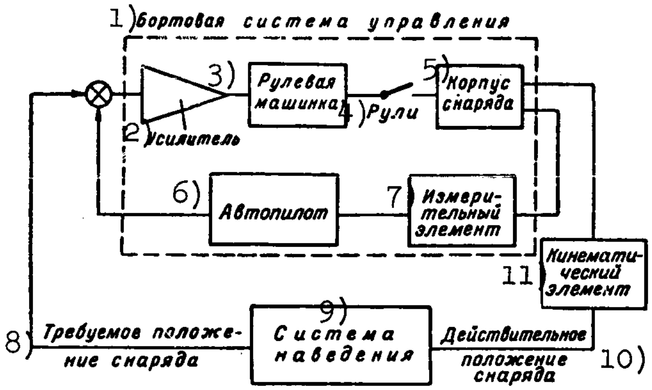

Fig. 24. Simplified block diagram of a missile control system. 1) On-board control system; 2) amplifier; 3) servomechanism; 4) control surfaces; 5) missile airframe; 6) automatic pilot; 7) measuring element; 8) required position of the missile; 9) guidance system; 10) actual position of the missile; 11) kinematic element.

This system is designed for the direct control of the missile; i.e., accurate and rapid execution of all commands with respect to changes in missile trajectory that are emitted by the guidance system, and assurance of stable missile flight over all sections of the trajectory in the absence of commands.

The guidance system, upon receipt of information on the rela-

tive position of the missile and the target, employs its computer equipment in accordance with the given guidance method and determines the most advantageous point of contact and works out control commands, which serve as control signals for the on-board control system.

The control signal from the guidance-system output is transmitted to the on-board control-system input, amplified, and converted into a substantial force which is able to deflect the missile control surfaces through an angle corresponding to the magnitude of the error signal. The control units act to make the turn, and as soon as the missile enters the correct course or the error signal vanishes (no command signal is transmitted), the control units revert to the normal (in other words, to the zero or neutral) position, and the missile will proceed in a straight line in the correct direction.

In cases of flight along a predetermined curvilinear trajectory, the error signal (mismatch at the system input) does not disappear.

Thus, there is a close interrelationship between the guidance system and the on-board control system, which influences the performance of the over-all control system of the missile.

The on-board control system is an important and vital link in the control system. The accuracy of missile guidance to the target depends on the quality of its characteristics. The on-board control system should assure missile stability and maneuverability in flight. In order to render the missile sufficiently maneuverable, the system should assure execution of turns with a certain minimum radius, i.e., it should be able to ensure the necessary lateral overloads (lateral or normal accelerations) of the missile. In some

cases the missile may have some internal stability, since the best maneuverability is attained in this case. In addition, the system should function normally under assigned (rated) longitudinal acceleration over a rather wide range of altitudes, velocities, and temperatures, and it should resist vibration, etc.

The on-board control system in terms of operating principle, is included in automatic control systems, since it automatically controls the position of the missile airframe. This system is a closed loop which has an input and output, as well as feedback from output to input. Since the so-called "external disturbance," i.e., the command from the guidance system, is an input to the system, and the output of the system repeats or follows-up the input command (the output is the position of the missile), such a control system is referred to as a follow-up or servosystem.

When a missile follows a given straight-line trajectory (when there is no error signal at the input of the system), the task of the on-board control system consists in maintaining the missile flight along the trajectory, i.e., stabilizing the flight. In this case, the on-board missile control system greatly resembles the automatic pilot of an airplane.

However, there is a difference between the automatic pilot of an airplane and a missile. The automatic pilot was originally designed for the purpose of relieving the pilot during straight-line horizontal flight. The basic task of such an automatic pilot was to react to random disturbances created by gusts of wind and to compensate for the steady-state disturbances created by side winds and faulty handling of the control units. Consequently, this type of automatic pilot was faced with the comparatively simple task of maintaining stability. Further improvements in the airplane auto-

pilot made possible changes in flight regime with respect to heading, roll, and pitch, by means of push-button control, including coordinated turns of the airplane, in which case a certain roll corresponds to the angular velocity of the turn.

The automatic pilot of the guided missile, which is an automatic stabilization and control system involving the use of the control units, differs from the airplane autopilot since it is designed to ensure missile stability as well as maneuverability.

Thus, the on-board control system serves as a flight stabilization system when there is no command signal, and with a command signal, it is a follow-up control system.

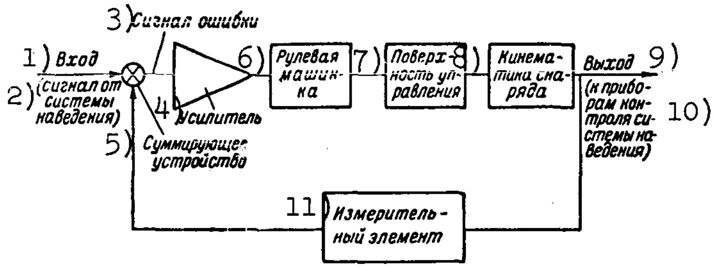

Fig. 25. Component elements of the on-board control system; 1) Input; 2) signals from the guidance system; 3) error signal; 4) amplifier; 5) adder; 6) servomechanism; 7) control surface; 8) kinematics of the missile; 9) output; 10) (to the monitoring instruments of the guidance system); 11) measuring element.

Generally, the on-board control system should stabilize and control the missile with respect to three coordinates: pitch, yaw, and roll, i.e., it should have three individual stabilization and control channels.

However, every missile does not require such a system.

For example, cross-shaped aerodynamic missile designs are most convenient, from the practical standpoint, if the on-board control

system utilizes only two channels for control: the pitch and yaw channels; the roll of the missile is stabilized by means of a separate stabilization system. Stabilization of missile roll in this case is necessary in order to avoid control errors which could arise because of roll. Roll results in the incorrect redistribution of the control signals among the channels. For example, when a command is sent for the change of missile trajectory with respect to pitch, this command will to some extent be unnecessarily controlled in another plane. To eliminate the mutual influence of the channels on one another (in order to eliminate cross-couplings), missile roll must be stabilized reliably. In come cases, complete roll stabilization is not required, i.e., it is sufficient to provide for low roll velocity on the part of the missile. In other cases, there need be no special missile stabilization system for roll, and in that case special equipment is needed to introduce correction signals (in the redistribution of commands) into the control signals of every individual channel to compensate for the roll.

In the case of airplane aerodynamic missile designs, where missile control is achieved by means of coordinated turns, there is no roll stabilization system, since a coordinated turn — for example, with respect to heading — calls for simultaneously coordinated motion with respect to roll and yaw. In this case, cross-couplings and special equipment are necessary, and these would distribute the control signal to the channels in appropriate proportions.

There can also be simpler control systems; for example, there can be single channel systems in which missile stabilization control is accomplished by means of only one channel, i.e., the yaw channel. Such a stabilization system is referred to as the automatic heading control system and is usually employed on ballistic

rockets.

Let us briefly study the structural designs of automatic pilots and their basic elements on guided missiles. The autopilot loop (Fig. 25), like that of any other follow-up system, consists of measuring (or sensing) devices, amplifier-converter, and follow-up devices.

The amplifier-converter equipment amplifies the weak control signal and converts it into a form suitable for the control of the corresponding power devices.

The follow-up equipment (in this case servo drives) directly affect the control units (control surfaces) thus changing the direction of missile airframe motion, i.e., they change, so to speak, the kinematics of the missile.

The measuring (or sensing) elements measure the quantities which characterize the actual position of the guided missile, and transmit corresponding signals to the input of the automatic pilot by means of the feedback system; these are added (actually, subtracted) to [from] the command signals from the guidance system (provided there is one) and they form the differential error signal or the control signal, which on having been amplified and converted, controls the control surfaces so as to reduce the error signal to zero.

Autopilot feedback loops, as in the case of any automatic control system, have various designations.

First of all, feedback closes the control loop of the automatic pilot and makes it possible to transmit to the system input the deflection magnitude of the object, measured by the sensing element; this quantity results from control for the purpose of comparing the actual position of the missile against the required position. In the absence of other feedback loops, these systems are re-

ferred to as single-loop systems. However, in order to improve the control process, additional or internal feedback can be transmitted to the autopilot, thus connecting one of the subsequent links of the system with one of the preceding links in order to control the degree of influence of an individual link on the performance of the over-all system. Such feedbacks are usually "rigid" (i.e., proportional to the quantity being controlled) and are referred to as parallel or correctional, and as a result of their utilization the system becomes a multiloop system.

In the case of more complicated autopilots so-called "flexible" feedbacks can be used, and these provide for the introduction of signals into the system that are proportional to the deflection angle of the missile in addition to the signals that are proportional to the velocity and acceleration of this deflection. The introduction of such additional signals enhances the ability of the stabilization units to return the missile more rapidly and forcefully to the required trajectory in cases of rapidly increasing missile deviation from the required trajectory.

Basically it is possible to introduce signals into the system not only of the velocity and acceleration of the measured angle, but also higher-order derivative signals.

Autopilot circuits and designs may vary in complexity, depending on the designation of the missile, its aerodynamic design, and the requirements of guidance accuracy.

When the requirements imposed on autopilots are less rigid, far simpler measuring elements as well as other intermediate links are utilized; a minimum number of feedback loops is used. Missiles equipped with such autopilots will, in practice, fly the desired trajectory in an unstable manner, oscillating with respect to this

theoretical trajectory ("twisting"). Although the wings and the empennage damp some of the missile oscillations along the trajectory, this fact in itself is completely insufficient. In order to achieve more stable flight, more complex automatic pilots consisting of more sensing elements and a greater number of feedback loops are necessary; this would ensure the smoothing out (damping) of these missile oscillations.

Autopilot measuring or sensing elements include potentiometers, gyroscopes, accelerometers (acceleration-measuring devices), as well as angle-of-attack and slip angle sensors, velocity head sensors, etc.

The potentiometers are employed in such purely potentiometric sensing elements as, for example, a servo-loop, where they measure the angle of control surface deflection, in addition to which they are also used as the measuring elements of the gyroscopic sensing elements.

The gyroscopes serve as the basic measuring elements of contemporary autopilots and they are used in a great variety of ways.

Two well known gyroscope properties are employed in gyroscope sensing elements:

1) the ability to maintain a constant direction in space for its axis of rotation, in the absence of an external disturbance;

2) the precession that appears as an external moment is applied, i.e., to deflect its axis of rotation at a certain angular velocity in the plane perpendicular to the plane of moment application.

Gimbal-suspended gyroscopes may exhibit a varying number of degrees of freedom. In the majority of cases, three-degree and two-degree gyroscopes are used.

A gyroscope in which the turning of the rotor about the axes

of rotation of the inner and outer frames of the gimbal suspension is not restricted in any way is referred to as a three-degree or free gyroscope. A gyroscope of this type makes it possible to change the turning angle of the missile about any axis. In view of this property, a gyroscope of this type is referred to as a position gyro.

One position gyroscope can measure two angles simultaneously, but it cannot measure the turn angle about the axis coincident (or parallel) with [or to] the main axis of the gyroscope. It is for this reason that at least two position gyroscopes have to be installed on a missile in order to measure three angles (pitch, yaw, and roll). For all intents and purposes this is what is actually done in practice: for the measurement of three angles, two gyroscopes are installed – a horizontal gyroscope – which measures the angle of pitch, Fig. 26a, and a vertical gyroscope which measures the angles of yaw and roll, Fig. 26b.

Whenever a gyroscope is deprived of one of its degrees of freedom, by being suspended on one frame, and the rotation of the frame is restricted by a spring, such a two-degree-of-freedom gyroscope will enable us to take measurements of the angular velocity of missile turn about any one of its axes. Such gyroscopes are referred to as precession or rate gyroscopes. Sometimes there are also referred to as gyrotachometers. A precessional gyroscope measures the angular velocity only with respect to one axis – the axis of the missing degree of freedom.

In addition to the above-mentioned basic gyroscope types, guided missiles can also utilize other gyros (for example, integrating gyros), with a varying number of degrees of freedom.

Accelerometers of various types are utilized in order to

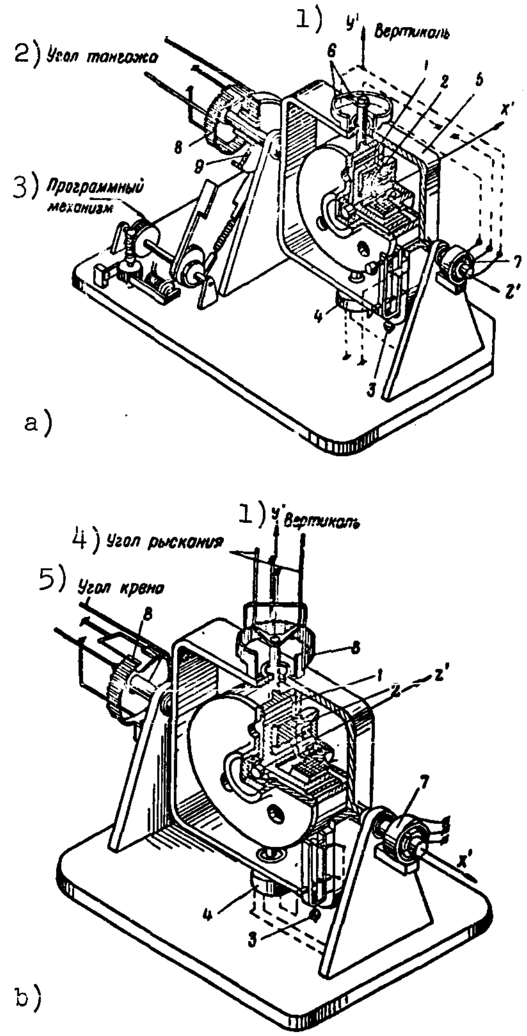

Fig. 26. Diagram and installation principle for the gyroscope on a guided missile. a) Horizontal gyro; b) vertical gyroscope; 1) gyroscope rotor; 2) stator winding; 3) pendulum of correction device; 4) electromagnet; 5) gimbal frame; 6) contact mechanism; 7) electromagnet; 8) potentiometer; 9) potentiometer pulley; 1) vertical; 2) pitch angle; 3) programming mechanism; 4) yaw angle; 5) roll angle.

measure missile acceleration, during missile motion or during random jolts or airframe vibrations. In order to measure linear accelerations, linear or pendulous accelerometers are employed. The simplest linear accelerometers are made in the form of a mass, sus-

pended on two sides by springs (see Fig. 99). As the missile accelerates, the mass of the accelerometer, positioned in a certain direction, with its tendency to remain stationary, shifts with respect to the frame of the instrument. This shift, which is proportional to the acceleration, is established by the potentiometer. In order to measure angular accelerations, angular or gyroscopic accelerometers are utilized. Recently, other, more accurate angular accelerometers have been developed.

The signals obtained from the measuring elements (usually from the potentiometers), are transmitted to the amplifier-converter equipment, which serves as the subsequent links of the autopilot, the so-called intermediate links. Depending on the design and complexity of the autopilot, the assembly and types of element in the intermediate links can be extremely varied. Let us examine an individual element of the amplifier-converter equipment, which can be utilized in the various channels of an automatic pilot.

It was pointed out earlier that in order to achieve better control stability, it is expedient to introduce into the autopilot the components of the control signal, proportional to the angular velocity and angular acceleration of the missile. For this purpose, instead of precessional gyroscopes and accelerometers, we sometimes employ differentiation of signals from a free gyroscope. This is accomplished by means of differentiating cells of differentiating loops. Since differentiation is accomplished more simply by means of differentiating cells operating on direct current, potentiometer sensing elements are also supplied from a direct-current power source.

The differentiating cell is a loop of an appropriately connected ohmic resistance and a capacitor (RC loop). For double differentiation (obtaining the second derivative), we use two dif-

ferentiating cells, connected in series.

Since a differentiating loop considerably weakens the signal, it requires further amplification. A-C amplifiers are primarily used to amplify the signal. Therefore, a direct-current signal having passed through the differentiating loop (or directly from the potentiometer) is converted by means of a converter into an A-C amplitude-modulated signal in accoreance with the direct-current input signal. The converter consists of transformers and selenium rectifiers. After amplification in the amplifiers operating on electron tubes or transistors, the control signal is transmitted to the servomotor (servomechanism). If an A-C signal were required for the control of the servomechanism, the amplified A-C signal would again be converted into a direct-current signal by means of a demodulator.

Such a process of control-signal frequency conversion is complicated and cumbersome, and consequently, magnetic amplifiers have recently been employed in automatic pilots; these amplifiers amplify the direct-current signals without any conversions. Utilization of magnetic amplifiers is also feasible because we frequently use amplifiers at whose input several signals are simultaneously applied, i.e., the so-called summing or differential amplifiers. In such cases, magnetic amplifiers are convenient, since every magnetic amplifier can have several input windings, which can be connected very simply for the addition or subtraction of signals. The output winding transmits the signal to the motor of the servodrive.

Relay amplifiers can also be utilized in automatic pilots. The type of amplifier, as a rule, is determined by the type of servodrive and the power sources.

Other elements and devices can be utilized in the intermediate links of an automatic pilot, and these are intended especially for

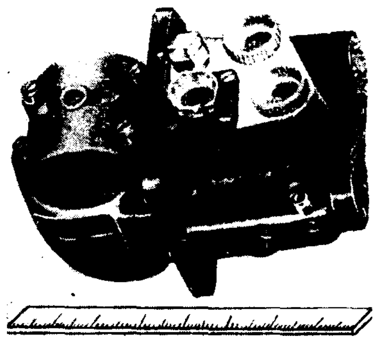

Fig. 27. Miniature hydraulic servomechanism of a guided missile.

the improvement of the characteristics of various links and the performance of the on-board control system as a whole.

The servodrives or servomechanisms are the follow-up units of the automatic pilot, and these deflect the control surfaces in accordance with the amplified and converted control signal. Missiles can employ hydraulic, pneumatic, or electric servomechanisms.

The hydraulic drive, in comparison with, for example, an electric drive has several advantages: it has greater overload capacity, requires less power in the case of a large hinge moment (force on the control units), etc. In comparison with the pneumatic system, the advantage of the hydraulic drive lies in the smaller time delay for the execution of a received command. In addition, the dimensions of the hydraulic mechanisms at the moment are quite small, which is vital from the standpoint of their utilization on missiles (Fig 27).

The selection of a servodrive is based on many factors, including the power sources. Therefore, for example, on missiles carrying a great variety of electric equipment it is expedient to use electric servomechanisms, and in the case of a high-pressure gas source it

is advantageous to use a pneumatic mechanism. Hydraulic and pneumatic drives are in greatest use. However, the pneumatic drive is preferred for missiles of small dimensions.

At the present time, missiles are using servomechanisms ranging in power from a fraction of a kilowatt to 40 kilowatts. Each servomechanism generally controls one control surface and therefore the number of servomechanisms is determined by the number of control surfaces on the missile.

The selection of a servodrive is also affected by the type of control units (aerodynamic surfaces, gas vanes, or rotating engines), which are selected on the basis of missile assignment, tactical and technical requirements, and consequently, its aerodynamic design as well.

Aerodynamic control surfaces are utilized when flight altitude and missile velocity in the atmosphere are sufficient for obtaining the corresponding aerodynamic forces necessary for missile control; gas vanes and rotating engines are used whenever missile velocity is low or the atmosphere greatly rarefied.

Deflection of missile control surfaces results in a change of its position in space. In other words, the output of the automatic-pilot loop represents a change in the elements of motion of the missile airframe: in the horizontal plane, it is the angle of yaw and the slip angle; in the vertical plane, it is the angle of pitch, angle of attack, and the slope angle of the trajectory. A change in these elements brings about a change in the slope of the "missile-to-target" line. A change of direction in the "missile-to-target" line is called the kinematic relationship or the kinematic element (see Chapter V), which is incorporated in the control system loop as a separate link.

The on-board control system, which is one of the most important component parts of the control system, can be characterized by a series of static and dynamic characteristics for the entire system as well as for each of the individual links.

The static characteristic of the system is the relationship between the output (controlled) quantity and the input quantity in the steady-state regimes of system operations. The shape of this function is usually curvilinear, and therefore, these characteristics are referred to as nonlinear. The slope of the static characteristic indicates the coefficient of amplification of the input quantity of the link or the system to the output. This factor is referred to as the gain constant of the system.

There are cases in which the automatic pilot is temporarily disconnected (for example, during missile acceleration), and then subsequently connected. At the instant the automatic pilot is connected or under conditions of powerful disturbances, the error signal can be rather great and the system will for some time exhibit a transient response, prior to eliminating the error, i.e., the missile will oscillate along the trajectory with its natural oscillation frequency. The functioning of the system in this mode is characterized by dynamic characteristics which are also referred to as transient characteristics. These include the time constant of the system (or of an individual link) which characterizes the length of the transient response of establishing the output quantity, or in other words the lag of the system, i.e., the delay in relaying the input signal to the output of the system, and they also include the frequency characteristics of this system, which determine the accuracy of input-quantity reproduction at the output in the case of forced oscillations at the input signal frequencies.

The frequency characteristic of the system (or link) is characterized by the width of the frequency passband within which the input quantity can be reproduced at the output with a tolerably small amplitude error. The width of the passbands of the individual links and the system as a whole must be kept at a minimum from the standpoint of interference and economy of power supply, whereas from the standpoint of high-quality dynamic system characteristics, it should be wide enough. Such contradictory requirements are satisfied by means of a compromise.

The inertial lag of this system determines the speed of reply or response to the input signal on the part of the system output. The ratio of the output quantity of this system (link) to the input quantity in nonsteady-state regime is expressed in terms of the gain constant (gearing ratio) or the transfer function of this system (link).

In analyzing any follow-up system, we study individually the characteristics of every link. Should a system or its individual links fail to satisfy the imposed requirements, a selection of transfer functions of individual links is undertaken by means of correction circuits – filters or equalizers.

The behavior or dynamics of the on-board control system can be described well by means of differential equations instead of transfer functions, with the equations making possible not only the determination of the transient characteristics, but also of many other features of the system (for example, stability, etc.). Such equations are called control equations. The solutions to these equations provide the stability conditions for the system, and this actually indicates the flight-stability conditions for the missile.

It is not absolutely necessary to solve complex differential

equations in order to determine the stability of a system; sometimes it is sufficient to utilize the stability criteria, which make it possible to judge the stability of a system directly in terms of the coefficients of the equation.

Regardless of the procedure, we arrive at the following stability conditions for the operation of the missile control system: the autopilot system and the control surface loop, in particular, must receive not only the signal that is proportional to the angle of missile deviation from the given course, but also the signals that are proportional to the angular velocity of missile deviation (i.e., the derivative of the initial signal) and in order to improve the control system, we should also provide for the introduction of signals that are proportional to the angular acceleration of the missile turn (i.e., the second derivative of the initial signal).

Every automatic control system is characterized by the magnitude of the error in the static and dynamic regimes.

The static error of the system is the difference between the steady-state value of the output (controlled) quantity and the value required in a steady-state regime (during stabilized flight). The static error can always be decreased and even eliminated (for example, by increasing the gain constant). Systems without a static error are referred to as astatic systems.

Dynamic errors arise during missile maneuvers, i.e., in the dynamic regime, and can be transient and steady-state.

A transient dynamic error of the system is the deviation of the actual value of output (controlled) quantity during the transient response (in the case of strong disturbances) from the steady-state or required value of this quantity.

A steady-state dynamic error is the deviation of the actual value

of output (controlled) quantity from the required value on completion of the transient response, or during a smooth change in regime (flight). The magnitude of the steady-state dynamic error is proportional to the angular velocity of the missile turn in space, i.e., the curvature of the trajectory.

As we have already pointed out, from the standpoint of control-system stability it is feasible to introduce derivatives into the system. The introduction of a derivative makes possible an increase of the gain constant, which results in a decrease in system errors and increases speed of missile response. However, infinite gain-constant increase is not possible because undesirable oscillations are produced, the band must be widened, and with lag in some links, the system may become unstable. Therefore, after the final selection of the type of follow-up system, correction devices are introduced and amplification is selected so as to obtain the appropriate frequency characteristics that will ensure minimum errors and sufficient system stability.

Control of cross-shaped missiles is accomplished by means of only two channels (pitch and yaw) independent of each other; stabilization is accomplished with all three channels (pitch, yaw, and roll), also independent of each other. Individual missile control with respect to two coordinates is possible because of the appropriate stabilization of missile position with respect to roll.

Let us first examine the stabilization system of the missile with respect to roll (Fig. 28). Roll stabilization is obtained by means of a free gyroscope (with a potentiometer pickup) installed on the missile so as to have the rotor axis horizontal and perpendicular to the longitudinal axis of the missile. The electric signal proportional to the produced angle of roll, obtained from the sensing element, is amplified and transmitted to the servodrive, which

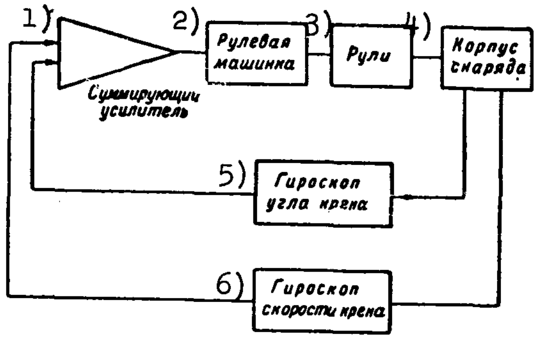

Fig. 28. Simplified block diagram of the roll stabilization system; 1) Adder amplifier; 2) servomechanism; 3) control surfaces; 4) body of the missile; 5) roll-angle gyroscope; 6) roll rate gyroscope.

deflects the control surfaces in various directions, similar to ailerons, with a resultant torque which counteracts the roll of the missile.

Such a system, in spite of the natural damping produced by the control surfaces, does not eliminate missile oscillations with respect to the zero position. In order to suppress the so-called weathercock oscillations of the missile it is necessary to employ artificial damping. Such damping can be achieved, for example, by means of a precessional (rate) gyroscope.

Whenever a rate gyroscope is used, it is installed in a position to measure the velocity of roll. The signal of this gyroscope, proportional to the velocity of missile roll, is transmitted to the servodrive after being amplified, and controls the ailerons on the basis of two signals. The signal from the rate gyroscope produces the moment which counteracts the moment produced by the free-gyroscope signal. Thus, the introduction of the rate-gyroscope signal slows down the roll of the missile during the period it traverses

the zero position and reduces missile rotation to zero. Missile oscillations will thus be suppressed, and the missile will be stabilized with respect to roll. Any desired characteristic of missile behavior with respect to roll can be obtained by the appropriate selection of the relationship between the signals of the free and rate gyroscopes.

The same effect can also be obtained in the case of damping, by the introduction of the velocity term (derivative) of the roll function, by means of differentiating the output signal of the free roll gyroscope. The latter method is simple and flexible.

The stabilization of the missile with respect to yaw and pitch (Figs. 29 and 30) is accomplished in the following manner.

For example, an accelerometer is installed in the yaw channel and this accelerometer is mounted as close to the center of gravity of the missile as possible for the purpose of greater measurement accuracy. The output voltage of the accelerometer, which is proportional to the acceleration in yaw, is transmitted to the servodrive after amplification, thus actuating the rudders in order to counteract any measured acceleration of the missile in the direction of yaw. Such a simple stabilization system for yaw will also display a tendency toward oscillation. Aerodynamic damping by means of wings and the empennage is insufficient, and therefore, as in the roll channel, artificial damping is produced by the use of a properly positioned rate gyroscope which is connected to enable its signal to counteract the yaw motion. In this case it is also necessary to establish the correct relationship between the signal from the accelerometer and the rate gyroscope to provide for rapid and reliable damping.

The control of the missile with respect to yaw and pitch in ac-

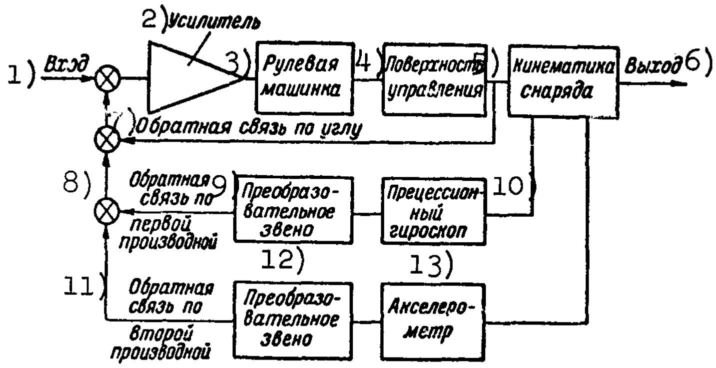

Fig. 29. Simplified block diagram of one of the channels of the automatic pilot (pitch and yaw); 1) Input; 2) amplifier; 3) servomechanism; 4) control surface; 5) kinematics of the missile; 6) output; 7) angle feedback; 8) first derivative feedback; 9) conversion link; 10) precessional gyroscope; 11) second derivative feedback; 12) conversion link; 13) accelerometer.

cordance with the guidance system signals is accomplished by means of applying these command signals to the output of the stabilization systems of the corresponding channels. The control process can be illustrated by the following example. Whenever the stabilization system is given a command over the yaw channel to turn to the left, corresponding to a given acceleration of 5 g, the control surfaces will deflect so as to carry out this command. The increasing acceleration will be measured by the accelerometer of the yaw channel, and the signal from the accelerometer will counteract the 5 g command, On completion of the transient response produced on receipt of the command, a steady-state control process (missile turn) will be produced and the missile will shift in the assigned direction at an acceleration of the order of 4.5 g. The difference of 0.5 g is the dynamic error of the control system, which is a result of the specific features of the system and its individual elements.

After the command has been carried out, the stabilization system

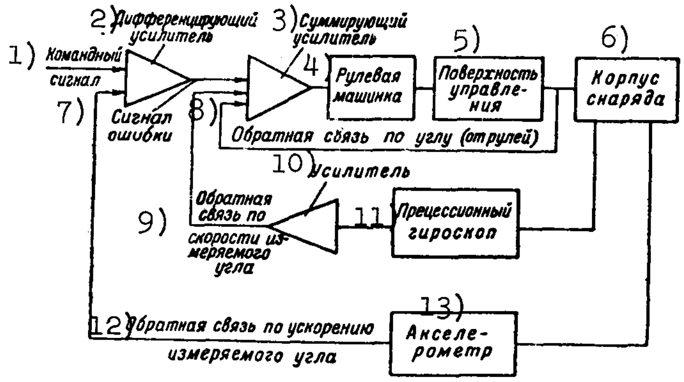

Fig. 30. Another version of a block diagram of one of the automatic pilot channels; 1) Command signal; 2) differentiating amplifier; 3) adder amplifier; 4) servomechanism; 5) control surface; 6) body of the missile; 7) error signal; 8) angle (for control surfaces) feedback; 9) measured angle rate feedback; 10) amplifier; 11) precessional gyroscope; 12) feedback of acceleration of measured angle; 13) accelerometer.

will provide for stable and straight-line missile flight along one of the coordinates.

The operation of the on-board control system is affected by many various factors either in the form of external or internal disturbances, which result in transient responses and regular steady-state oscillations of the system, or they consist of harmful couplings in the autopilot circuit, and these have a negative effect on the normal operation of the system. All these factors can result not only in considerable errors in guiding the missile to the target but can also have a great effect on the flight stability of the missile. There are various methods of combating and eliminating the harmful influences of these various factors; however, it is not always possible completely to eliminate their harmful influence, and some still

interfere with the normal operation of the system. Let us examine several of these factors and point out the known methods of eliminating their undesirable influence.

The external factors (disturbances) can include the following: deviation of the missile from the assigned direction at launch, turning on of the on-board control system subsequent to launch, jettisoning of the booster, great longitudinal and lateral acceleration, wind, changes in control-surface effectiveness, noise and interference introduced into the autopilot by the guidance system, etc.

The internal factors (or disturbances) include the following: buckling and vibration of the missile airframe (a phenomenon of aerodynamic elasticity), warping and torsional vibrations of the missile airframe, oscillations, internal resonance, deformation of control surfaces (aerodynamic elasticity of the control surfaces), incorrect installation of the measuring instruments, manufacturing tolerances, etc.

The shortcomings of the circuit include: random cross coupling and feedback, nonlinearity of link characteristics, overload and lagging of the individual links of the system, instability of the power sources, the effect of temperature and changes in external conditions on the performance of the individual elements of the on-board equipment, etc.

With respect to the time at which the autopilot is put into operation, control systems can be constructed according to various principles: in some cases, the autopilot is turned on prior to launch, and in other cases afterward. Often, as a result of disturbances that may result from launch overloads (initial acceleration), switching on of the on-board power sources and other mechanisms, jettisoning of the booster, as well as because of other reasons, it

is not advisable to transmit signals from the guidance system which is sometimes in operation prior to launch, to the control units, in order to avoid deflecting the missile. These command signals are transmitted to the autopilot by means of some time-delay device (relay switch) only after acceleration of the missile has been completed. From the standpoint of guidance, at this time the missile will by no means be in its exact position, and its guidance errors will be great. At the instant the autopilot is turned on, it may be subjected to a great error signal and cause a substantial transient response and such lateral acceleration as would either destroy the missile or disturb its stability. In order to eliminate this danger in the autopilot, various types of limiting devices are used, and these weaken the great autopilot input signal.

As the altitude of the missile increases, reaction (response) to the same control signal is considerably decreased due to the decrease in air density, and in view of the necessity of flight with with great overloads (acceleration), the missile may assume angles of attack at which it will become unstable and control will become ineffective. Therefore, it is necessary to install equipment limiting the acceleration of the missile at great altitudes. By the same token, it is necessary also to consider changes in missile velocity.

In many cases, the command signal from the guidance system (radar guidance systems, in particular) is introduced into the autopilot together with various types of noise and interference. In this case, the signal is very weak against the background of noise, in addition to being able to fluctuate (die out). In such cases, the missile may lose the target. The condition can be improved by means of filter circuits which will filter signals of unnecessary frequencies. Such filters can be installed in the guidance system links

as well as in the autopilot itself. However, it should be borne in mind that every filtering process introduces a signal delay. From this standpoint, various on-board control system versions are possible.

It is possible to develop a system which will receive the control signal together with the noise after some insignificant filtration in the guidance system. In this case the autopilot will receive the commands with a slight delay; however, the discrimination between the control signal and the additional noises will have to take place within the circuits of the autopilot itself. This leads to the following results: 1) the autopilot circuits may become saturated with noise signals and lose their effectiveness with the appearance of the useful signal, and 2) in the transmission of noises through the autopilot to the control surfaces, undesirable oscillations of the missile with respect to pitch and yaw may be produced, and these will increase frontal resistance and reduce the aerodynamic features of the missile.

Another version of the system may be selected; in this version, strong filtration takes place in the guidance system, and the autopilot receives a sufficiently "clean" signal. The unavoidable signal delay in this case can result in the missile reacting slowly to the command.

Consequently, both versions of the system can result in a "closest approach" error. In the first case, because of the error in establishing the position of the target, and in the second, because of the delay in maneuvering. Thus, the basic structure of the control system is actually determined in every individual case.

We should consider one more factor which affects the control-system operation as the missile approaches the target. As the distance to the target decreases, the line missile — target begins to

change rapidly (the influence of the kinematic element becomes more apparent). With some guidance methods, before striking the target the missile must develop unusually great angular velocity, which calls for high lateral acceleration. If missile maneuverability is limited, this is impossible. The missile becomes unstable, and the "closest approach" error unavoidable. Calculations show that should the control circuit be disconnected sometime prior to striking the target (several seconds), and should the autopilot be used to assure straight-line flight, the "closest approach" error will be smaller. However, this is not the best solution. A better solution is the selection of another guidance method, which will not cause high overloads during the last guidance stage and, consequently, will not require the disconnection of the on-board control system before striking the target.

The phenomenon of aeroelasticity comes about as an elastic deformation of the missile airframe under the action of aerodynamic loads, and particularly high acceleration which causes the buckling and vibration of the missile airframe. Such vibrations can be produced as a result of aeroelastic deformation of the control surfaces. These oscillations can be picked up by the sensing elements of the control system (accelerometers and gyroscopes), resulting in harmful couplings and feedback, in addition to the mutual influence of control channels on each other; this will result in undesirable missile maneuvers in various directions. The same effect can be produced by over-all and local vibrations, brought about by engine operation, wing flutter, servodrive lag, etc.

Individual structural elements of the missile and even individual sections of the missile can have various natural frequencies, and these result in local internal resonances which, through the

control system, also have a negative effect on the stability of the missile.

Various methods are employed for the purpose of eliminating the harmful influence of such phenomena. First of all, an effort is made to mount and position the sensing elements of this system so that deformations and the various missile oscillations affect them as little as possible. In addition, an effort is made to distribute according to frequency the various elements (and channels) of this system that have a harmful effect on each other, i.e., to select the natural resonance frequencies of the elements in such a way as to have them differ from each other (at least by a factor of three). Another measure is the introduction of mechanical and electrical filters into the individual links of this system in order to weaken the undesirable and harmful frequencies In addition, various correction circuits are used (smoothing filters, tachometer generators, integrating circuits, auxiliary feedback circuits, etc.) in order to improve the characteristics of the individual links of this system, and to introduce some correction factors into the control-system equation. However, it is always better to eliminate some local resonance than to adapt it to the characteristics of the system.

Sometimes, rather than improve the characteristics of the on-board control system, which are the result of aeroelasticity and missile airframe vibrations, an appropriate missile shape is selected. At any rate, the design of the on-board control system of the missile is not divorced from the aerodynamic characteristics of the missile. However, the following considerations are kept in mind: the missile must not necessarily be statically stable (i.e., aerodynamically stabilized); the stability of the missile can be assured by means of the on-board control system.

In addition to the above methods of improving the operation of the on-board control system, the high-quality elements of this system are used, in particular, the electronic apparatus; highly stabilized power sources are employed, the equipment is hermetically sealed, etc.

It should be noted that in utilizing guided missiles with launching boosters, a separate on-board control system may be required for operations during the acceleration period. In this case, the system can be completely independent of the main control system, including the power sources, servodrives, control surfaces, and other elements, if the control operation during the acceleration stage and during the approach to the target differ greatly from one another.

Chapter IV

CLASSIFICATION OF CONTROL AND GUIDANCE SYSTEMS

As has been pointed out, the guidance system is a part of the control system. Depending of the classification and designation of the missile, the system may vary in terms of operating principle and complexity. Unlike the on-board control system, which, of course, is located only on the missile, the instruments of the guidance system can be located outside of the missile (on the ground, on a ship, airplane, or on another missile).

Generally, the guidance system determines the position of missile in space with respect to the target, computes the required flight trajectory, and in connection therewith develops command signals for missile trajectory changes, which thereafter are transmitted to the on-board control system, ensuring the flight of the missile along the required trajectory. As a rule, the control systems have a greater influence on missile guidance accuracy toward the target than other parts of the control system.

Depending of the tactical mission of the missile, the nature of its target, and the distance to the target the missile control can be achieved by various control systems, which are designated on the basis of the operating principle of the missile guidance systems. From this standpoint all control systems, as well as their guidance systems, are divided into three basic groups (Fig. 31):

1) self-guidance systems

2) remote-control systems (long-range control)

3) autonomous control systems

These three groups of control systems vary substantially among themselves in estabilishing interconnections during the guidance process, between the missile, the command point, and the target, and they also vary with respect to range, principles of guidance-system design and operation, and other characteristics. Each group of control systems is subdivided according to the type of guidance system, which is desgined of the basis of varying physcial principles which are achieved in various ways, from the technical standpoint.

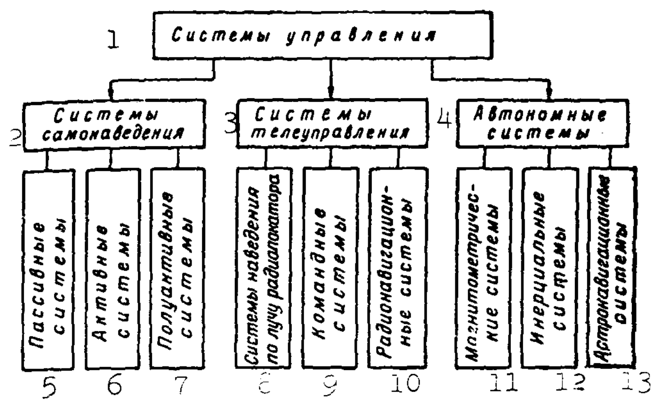

Fig. 31. Classification of control and guidance systems 1) Control systems; 2) self guidance systems; 3) remote control systems; 4) autonomous systems; 5) passive systems; 6) active systems; 7) semi-active systems; 8) radar guidance systems; 9) command systems; 10) radio navigation systems; 11) magnetometric systems; 12) inertial systems; 13) astronavigation systems.

Missiles equipped with self-guidance systems carry equipment which automatically tracks the target, as a result of which the position of the target with respect to the missile is automatically determined. This is performed by means of a self-guidance head, the basic element of which is the target coordinator. When the missile shifts with respect to the proper direction, i.e., when an error signal is formed, the target coordinator develops command

signals that are transmitted to the autopilot, which by means of the control units ensures constant tracking of the target up to the point of contact.

In the case of guided missiles equipped with remote-control systems, the position of the missile with respect to the target is determined in the majority of cases by instruments installed at a particular point of control, thus shaping suitable command signals which are functions of the guidance error, and these signals are subsequently transmitted to the missile over communications lines. These commands are received by the missile and converted into forces which act on the control units of the missile so as to enable the missile to correct its trajectory and be guided to the target. With certain remote control systems, determination of missile position with respect to the target or command point as well as the shaping of command signals regarding trajectory changes, can be carried out in the missile itself on signals from ground guidance stations.

Autonomous control systems, completely concentrated on the missile, continuously measure the shift of the missile from the assigned and programmed flight trajectory, thus automatically correcting the flight direction in order to guide the missile into the area of the target with a minimum error.

Let us examine briefly the operating principle of each of these control groups.

Self-guidance systems. For the normal functioning of self-guidance systems, each one of these systems must first of all be able to locate the target, or in other words, distinguish it from the surrounding background. For this purpose, the target must necessarily differ in its physical characteristics from the

surrounding background or other objects, i.e., it must exhibit sufficient energy (power) contrast with respect to the background. In general, self-guidance of a missile to a target is possible since the target usually emits or reflects some type of energy which can be received by the receiving equipment on the missile. The following are the possible types of energy: heat (infrared rays), light, sound, static electricity (ionized stream), electromagnetic rays, etc.

Many targets can serve as heat (infrared) sources: ships, airplanes (particularly jets), metallurgy and similar plants, and also the smokestacks of plants at other enterprises. The head of a long-range ballistic missile also emits considerable heat, since it develops heat during its high-velocity flight in the lower and middle layers of the atmoshere. The heat radiation is received by special optical instruments, including sensing elements which react to infrared rays. Such instruments, which follow a target upon locating it by means of its heat radiation and continuously determine the direction toward the target, are referred to as heat direction finders. Self-guidance systems which employ the heat contrast of the target and similar guidance instruments are referred to as thermal or infrared self-guidance systems. The effective range of such systems depends on the temperature and the surface area of the target emitting the radiation, the sensitivity of the receiving equipment, and meteorological conditions. This range fluctuates between several kilometers up to ten kilometers.

There are targets that either emit their own light (projectors, navigational lights on ships, etc.), or reflect solar light, moon light, or artificial lighting (roads, bridges, airport runways, ship decks, etc.) in ways other than the surrounding

background. These light contrasts of the target can be utilized for optical location of targets with optical self-guidance systems. In such cases, sensing elements which react to light rays are employed in the receiving equipment. The effective range of such systems depends on the contrast properties of the target, the time of day, weather, and it may range from several hundred meters to several kilometers. It is for this reason that optical self-guidance systems have not come into widespread use.

Some targets, as for example, airplanes and ships of various classes are rather powerful sources of sound. The noise of a motor or of an airplane reaction-trust engine, as well as the operating mechanisms of a ship, can be detected at considerable distances. Guidance systems designed on the principle of target sound or noise reception are referred to as sound direction finders or acoustical self-guidance systems. It becomes difficult to use such systems for missiles aimed at targets in the air because of the low speed of sound propagation, which causes the missile to be guided to a point somewhat beyond the target rather than at the target itself, and this complicates guidance, particularly in the case of supersonic target velocities. In addition, missiles themselves create a noise during high-velocity flights, thus disturbing the operation of the system. However, the effective range of hydro-acoustical systems, employed in the place of self-guided underwater missiles, may be fully adequate for utilization.

Radar self-guidance systems have become most popular, since many vital military objects are either themselves sources of electromagnetic radiation or reflect radio waves well. Objects emitting their own radio waves include radar stations of various designations, radio-interference stations, aviation guidance posts,

airport radio towers, reaction-thrust missile control points, etc. Such targets, can be located with respect to the missile by means of a directional receiving antenna.

For the self-guidance of missiles to targets reflecting electromagnetic energy, these targets must exhibit radar contrast with respect to the surrounding background, i.e., they should reflect radio waves better than the surrounding space or objects. Such targets include metal structures or other objects containing metal parts; for example: ships, airplanes, railroad bridges, factory buildings with metal roofs, etc. To find such targets, they are bombarded by radio waves from a special radar transmitter, and the signals reflected from the target are picked up by a receiver with a directional antenna installed on the missile. The basic advantages of radar self-guidance systems are their low dependence on meteorological conditions and a relatively great effective range, which may attain several tens of kilometers.

On the basis of the principle of employing energy emitted or reflected by the target for the purpose of guiding the missile, self-guiding systems are subdivided into three basic categories: passive, active, and semi-active.

In the case of passive self-guidance (Fig. 32) the missile is guided to the target which is itself the source of the emitted

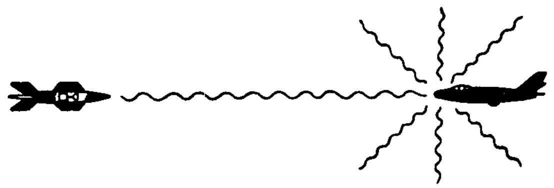

Fig. 32. Operating principle of the passive automatic guidance system

energy. In this case, only receiving equipment is necessary on the missile, in order to receive signals coming from the target, where-

as a transmitter for the purpose of bombarding the target is not necessary. The effective range of passive systems is small. A typical example of a passive self-guidance system is the infrared system.

In the case of active self-guidance (Fig. 33) the missile itself radiates energy to the target, and this energy on being reflected by the target is picked up by the receiving equipment of the missile. In such a case, the missile must necessarily be equipped with a transmitter, in addition to a receiver. The in-

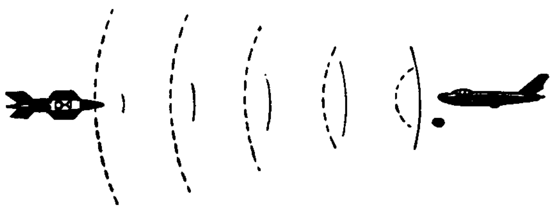

Fig. 33. Operating principle of the active self-guidance system

crease transmitter power increases the dimensions and weight of the on-board equipment, thus making it impossible for the missile to be equipped with a powerful transmitter. Consequently, the effective range of the active systems cannot be substantially increased. Radar self-guidance systems, among the active systems, have found practical application.

In the case of semi-active self-guidance (Fig. 34) the transmitter is not located on the missile itself, but outside (on the ground, a ship, an airplane), and consequently, it can be powerful and at great distances from the target. In such cases, only receiving equipment is installed on the missile. The effective range of semi-active self-guidance systems is greater in comparison with the effective range of active systems. Consequently, radar semi-active self-guidance systems have been used more widely than the

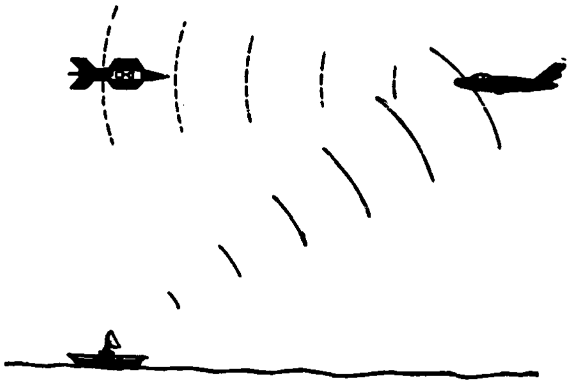

Fig. 34. Operating principle of the semi-active guidance system

active.

Remote control systems. The radar guidance system (Fig. 35), which belongs to the remote-control systems group, is closely related to the radar self-guidance systems in view of the principle of isolating the error signal. In this system the control point

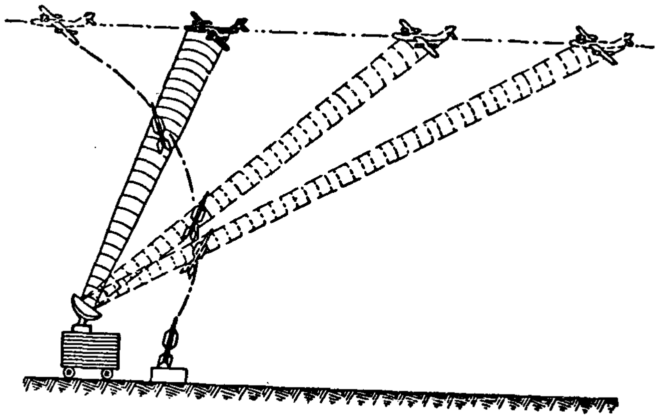

Fig. 35. Operating principle of the radar guidance system

(on the ground, ship, or airplane), is equipped with a radar track-

ing device with conical scanning. On locating the target, the radar beam keeps tracking the target, and the missile, equipped with a receiver unit and other guidance equipment, tends to proceed along the axis of the beam directly to the target. Should the missile shift with respect to the axis of the beam, the guidance apparatus will automatically, without any special signals from the command point, determine the shift and work out commands forcing the missile to return to the axis of the beam. Thus the missile is automatically guided toward the target along the beam which continuously tracks the target. In this case, the missile is constantly within the line "control point-target" (the three point method).

The other guidance method along a beam (guidance toward a precessed point) employs two radar units, one of which tracks the target and transmits all the target data to a computer, which works out a program of beam motion from the second radar unit along whose axis the missile moves. This variation of the system is sometimes referred to as the beam rider system.

Consequently, the beam-rider guidance systems can have two variations: single-beam (one radar unit) and double-beam (two radar units).

The beam-rider system differs from the self-guidance systems inasmuch as the missile, although self-guided, moves along the beam blindly, regardess of whether there is a target in space or not, as a result of which there is no target coordinator, while with self-guidance systems the missile can "see" the target, track it, and independently pursue it. Although the radar-beam guidance system may at first appear to be somehere between the self-guidance systems and the remote-control systems, it actually belongs to the latter.

Command systems. Two radar units can be used differently from the case of the beam-rider guidance method, i.e., one of the radar units is used to track the target, whereas the other tracks the missile; the data from the two radar units are transmitted to a computer which uses this information to work out coded control signals (commands) which are then automatically transmitted to the missile by means of a special command radio transmitter or directly along the radar beam employed to track the missile in order to guide the missile to intercept the target. A guidance system of this type is referred to as a command system and is also included in the group of remote-control systems.

There are many variations of command systems (Fig. 36), but they are all characterized by the necessity of having two communication lines between the command point and the missile (see Fig. 39). One line is assigned to the observation of missile motion with

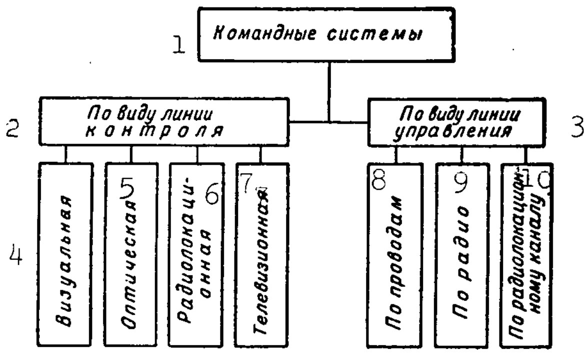

Fig. 36. Classification of command-guidance systems
1) command systems; 2) for monitoring line; 3) for control line; 4) visual; 5) optical; 6) radar; 7) television; 8) wire; 9) radio; 10) radar channel.

respect to the target (monitoring line) and the other to the transmission of commands to the missile should the missile deviate from the calculated trajectory (guidance line). Sometimes, both lines

can be housed in the same instrument. The monitoring as well as guidance systems can vary. Monitoring systems may be visual (the naked eye of the operator, optical sighting, radar, television, whereas the transmission of control commands can be accomplished over wires, radio, or over the radar channel. Basically, the commands to the missile can be transmitted by means of the optical communications link (light or infrared rays); however, one of the basic shortcomings (limited range and unreliability) is keeping it from being employed at the present time.

Radionavigation systems. Radionavigation guidance systems can be employed for the guidance of guided missiles. Thus, for example, to guide the flight of long-range missiles it is quite feasible to employ pulse or phase hperbolic and circular systems of navigation. In this case (Fig. 37) three or four ground stations transmit synchronized signals, and the receiving equipment with its automatic guidance apparatus measures the time difference between the receipt of signals from the two stations (or both pairs) in the case of the pulse system, or compares the phase of the received signals in the case of phase systems, converting the data into data on the position of the missile. The comparison carried out on the missile of the assigned trajectory against actual trajectory makes it possible to obtain the error signals which correct the motion of the missile.

The radionavigation systems whose guidance process does not involve the transmission of any commands and in which the missile guides itself in accordance with an assigned program, nevertheless belongs in the group of remote-control systems, since they are fully dependent on ground equipment – the guidance station.

Thus, the remote-control systems can also be broken down into

three categories: the beam-rider guidance system, the command system, and the radionavigation system.

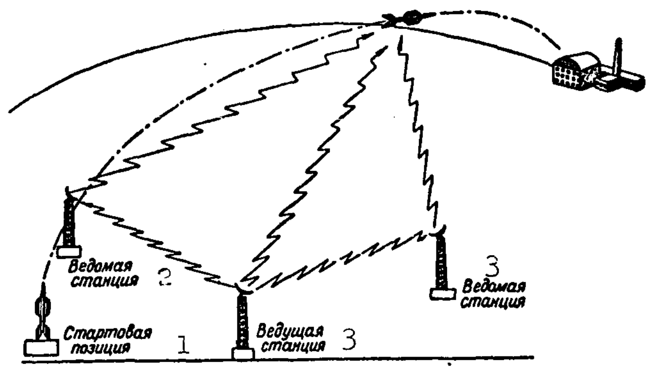

Fig. 37. Operating principle of radionavigation guidance systems. 1) Launching position; 2) controlled station; 3) master station.

Autonomous systems. Guidance of long-range missiles, including intercontinental missiles, may involve autonomous control systems which utilize the known laws of mechanics and the physical characteristics of the Earth and the Universe.

These systems include magnetometric, inertial, optical, celestial-navigation, and radio-astronavigational systems.

A magnetometric missile guidance system employs the phenomenon of terrestrial magnetism. The magnetizing force of the earth's field and other components of terrestrial magnetism can be measured by special instruments. The values obtained can be used to determine the position of the missile with respect to the surface of the earth. Should a missile be equipted with automatic equipment to measure the elements of terrestrial magnetism, such a magnetometric system can be then employed for the guidance of the missile to the target, provided the elements of the magnetic field at the position of this target are known.

The operating principle of the <u>inertial system</u> is based on

utilization of the inertial properties of gyroscopes, which tend to retain their axis of rotation in a fixed position with respect to space and consequently enable us to create gyroscopically stabilized platforms that hold a platform on which two or three accelerometers are mounted to measure accelerations in two or three mutually perpendicular planes in a horizontal position at all times. Two accelerometers measure lateral accelerations, and, after double integration, enable us to determine the deviation of the missile from its specified programmed trajectory with respect to altitude and direction. The third accelerometer measures the missile's acceleration along its trajectory, which, after single or double integration, enables us to determine the speed of the missile and the distance that it has traveled. Exact allowance for the distance traveled is necessary for exact determination of the missile's position. The distance traveled is figured by a computer. In the last analysis, the program mechanism guides the missile to its target at the optimum diving angle. The precision of the system depends on the precision of the accelerometer measurements and the precision with which the platform is stabilized.

The <u>celestial navigational system</u> is based on the principles of navigation by the heavenly bodies. Such a system receives data from a telescopic device (sextant) that is capable of automatically tracking one or two fixed stars. The telescopes that track the stars are mounted on a gyroscopically stabilized platform in the missile. The altitudes of the celestial luminaries, which are the angles between the line of sight to the luminary and the plane of the observer's horizon, are measured by automatic observation. The position lines of the missile and its position are determined from the observational data. The flight is completely programmed before launching, and the necessary reciprocal positions of the missile and the stars selected

are determined for each moment of its path. At a certain time, the program mechanism breaks off transmission of signals to the autopilot from the telescopes and guides the missile to the target. The precision of such an optical celestial-navigation system may be higher than that of an inertial system.

Thanks to the rapid development of radio astronomy, it has become feasible to build a radio-celestial navigation and homing system that uses a radio sextant as the basic instrument of the system. The radio sextant receives electromagnetic energy radiated by the heavenly bodies and automatically follows these bodies. Having been set up on the missile's gyroscopically stabilized platform, the radio sextant can issue a continuous flow of data on the altitude of the heavenly body being tracked in a manner adequate for control of the missile.

All autonomous control systems are basically gyroscopic systems in which auxiliary signals from so-called correcting devices are fed to the autopilot as the missile deviates from its programmed trajectory. These instruments are accelerometers in inertial systems and sextants in celestial-navigation systems, and hold the missile on its computed trajectory.

All autonomous systems are grouped among the programmed control systems, since the controlling equipment of such systems includes, in addition to elements that measure the missile's motion, program devices. Program devices or programming elements are also found in other homing systems, such as single-radar command systems, hyperbolic radio-navigation systems (the case of guidance on a prespecified straight line), etc. However, they are not indispensable elements or distinctive criteria for these systems. In autonomous system, on the other hand, program devices are necessary; they function here as homing systems. It can therefore be stated that all autonomous control

systems have program-type homing systems.

* * *

All of the homing systems considered above can be classified differently.

In accordance with the presence of a link between the missile, the target, and the command point, all control systems are classified into three groups:

1) semiautonomous systems (Fig. 38) – systems with one line of communication between the missile and the target and no communication line between the missile and the command point; automatic homing systems belong to this group;

2) nonautonomous systems (Fig. 39) – systems with two lines of communication between the missile, the command point, and the target: a control line and a telemetry line; this class of systems includes remote-control systems; an exception here is the radio-navigation homing system, in which one communications link (that with the target) is absent, so that this system cannot home the missile on to a moving target;

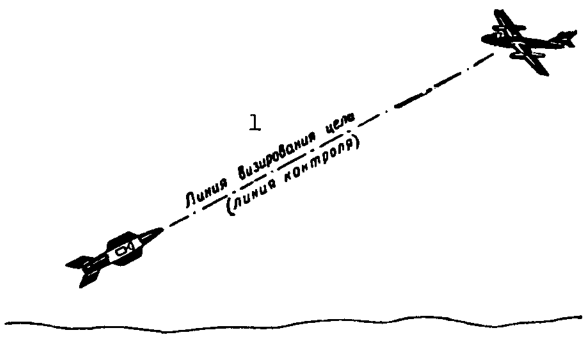

Fig. 38. Communications line between missile and target in automatic homing system (semiautonomous systems). 1) Line of sight through target (telemetry line).

3) autonomous systems (Fig. 40), in which there are no communication lines between the missile and the target or the command point; these systems home the missile only onto fixed targets by a preset program computed on the basis of the missile's position relative to the target at the launch time; consequently, they are known as programmed systems.

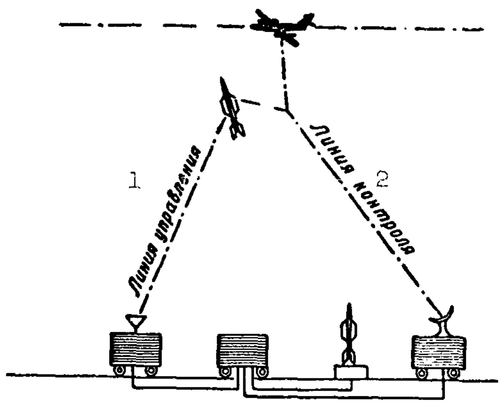

Fig. 39. Communications lines in remote-control systems (nonautonomous systems). 1) Control link; 2) telemetry link.

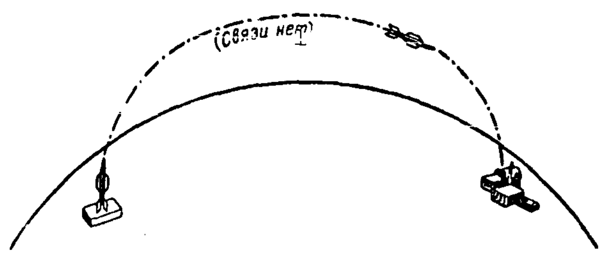

Fig. 40. Absence of missile-to-target and missile-to-command point communications links in autonomous control systems. 1) No link.

On the other hand, the first two groups – the semiautonomous and nonautonomous systems (except radio-navigation systems) – can home missiles to both moving and fixed targets.

On the basis of technical criteria, systems may be broken down basically into optical (light and infrared techniques), acoustic, electronic, magnetometric and inertial (gyroscopic) systems.

On the basis of their tactical properties, the systems may be classified as short-range systems, medium-range systems, and long-

range systems.

Short-range systems include all automatic-homing systems, beam-riding systems, and the majority of command systems.

The medium-range systems include some command systems, including television types and certain radio-navigation systems.

The long-range systems include hyperbolic radio-navigation systems and all autonomous control systems.

In considering a classification of homing systems on the basis of their tactical properties, it is necessary to draw a line between the concepts of the long-range missile and the long-range homing system. In those cases where the missile is controlled by a single physical system over the entire extent of its flight, the concepts of missile range and system range are identical. But sometimes these concepts diverge. For example, certain long-range missiles (usually ballistic) are controlled over a relatively short segment of their flight, while their effective range may be long. Such missiles are brought to a certain point on the computed trajectory by means of short-range or medium-range systems, and then enter free flight in accordance with the laws of ballistics, sometimes with slight subsequent correction of the trajectory on its descending branch.

Various types of guidance systems are used to conduct ballistic missiles to a computed point on the controlled segment of the trajectory. Most frequently, radar-type command systems consisting of a homing radar (beam-riding system), a radar operating on the Doppler principle to measure the missile's velocity (telemetry system) and a computer that generates commands to correct the missile's trajectory and shut off its engine, are used for this purpose. Such systems are known as control systems with trajectory correction. In more recent ballistic-missile developments in the USA, autonomous inertial systems

have come into use; these do not require ground equipment to control the missile in its flight.

Each of the guidance systems considered here has its advantages and disadvantages. Essential shortcomings that limit or completely exclude their application are inherent to certain systems. Each system may be evaluated in terms of the extent to which its properties approximate the <u>hypothetical ideal</u> guidance system, for which the following specifications can provide a criterion. The system must

1) work at any point on the Earth's surface;
2) work at any time of day and in any type of weather;
3) not emit signals that be detected by the enemy;
4) have total noise suppression;
5) be capable of deflecting the missile from a straight-line course by a considerable margin;
6) have unlimited range capability;
7) have no altitude limitations;
8) have high precision;
9) control an unlimited number of missiles;
10) not require complex ground equipment;
11) not require preliminary surveying;
12) be reliable;
13) have small dimensions and low weight in the on-board apparatus.

No known system satisfies all of these requirements fully. Theoretically, the inertial system comes closest at the present time to the ideal system, but in spite of a whole series of improvements, it is still plagued by many technical problems that must be solved if the desired results are to be obtained as regards precision and other performance indices.

<u>Combination of systems</u> is a practice widely employed at the pre-

sent time to make the closest possible approach to the above specifications. Homing-system combination can be effected in the widest imaginable variety of ways, but the most common is to combine two systems of which one, which possess a number of advantages (basically, the necessary effective range) but has inadequate precision, is used to home the missile on the basic segment of the trajectory, while the other, which has higher precision, is employed in the final homing stage.

Chapter 5

FLIGHT DYNAMICS OF GUIDED MISSILES. METHODS OF HOMING MISSILES ONTO TARGET AND POSSIBLE FLIGHT TRAJECTORIES

A guided missile of any class must reduce its target; for this reason, the function of any homing system is to guarantee that the missile will strike or bracket the target with the smallest possible miss distance. To discharge this function, the homing system must have a special apparatus for generating control signals that will direct the missile along a trajectory that ensures that it will strike the target.

Since the missile can be guided, there are, in principle, an innumerable number of trajectories that will provide for the missile hitting the target. In practice, however, we make an effort to select that trajectory which, under specified firing conditions, will guarantee the most reliable destruction of the target. In selecting the most suitable trajectory for the flight, we take into account not only the probability of target reduction, but also a number of other factors, such as the shortest flight time, maximum angular velocity, maximum normal accelerations, flight stability, etc. All of these factors are of essential importance in choosing and planning missile control systems and their individual units (homing systems, on-board control circuit, control-surface circuit, and so forth).

Thus, the trajectory along which a missile moves will not be

arbitrary, but will be limited by certain conditions that ensure the desired homing behavior. The law describing this behavior is known as the homing technique. From a kinematic viewpoint, the homing technique determines the theoretical trajectory of the missile's flight.

The homing technique selected is realized by means of a computing device incorporated in the homing system.

The computing device receives information on the relative positions of the missile and the target, and on the velocities and directions of their motion, and uses this information to compute the desired trajectory of the missile's motion and determine the must favorable point of encounter. The result of the calculations is then converted into control commands, which go into the on-board control system, which then guides the missile in accordance with the preset law.

In accordance with the type of homing system, the computing devices may be situated on board the missile or at the control point.

The information entering the computing device may be in the form of angular positions, angular velocities, or ranges. The computing operations carried out by the computing devices will differ for different systems and different homing techniques. A typical problem of the computing instrument in many systems is to compute the angular velocity at which the missile – target line displaces in space; this is a determining factor in examination of homing techniques.

As it affects automatic-homing systems, the missile – target line is known as the target-sighting line or the aiming line. In this case, the sighting line is determined by the target coordinator, which is mounted either fixed or movable in the nose of the missile.

The position of the missile in space relative to the coordinate system adopted is, as we have already noted, characterized by a series of angular coordinates in different planes. When the missile is

homed onto the target, its position is evaluated not only with respect to the coordinate axes, but also relative to the target, so that a number of additional characteristic angles make their appearance. All of these angles for the vertical plane can be seen in Fig. 41. Here the new angles are as follows: the angle of target-position error or the angular homing error ε, which is the angle between the geometrical axes of the missile and the missile-to-target direction and the missile-to-target line angle σ, which is the angle between the coordinate axes and the missile-to-target direction.*

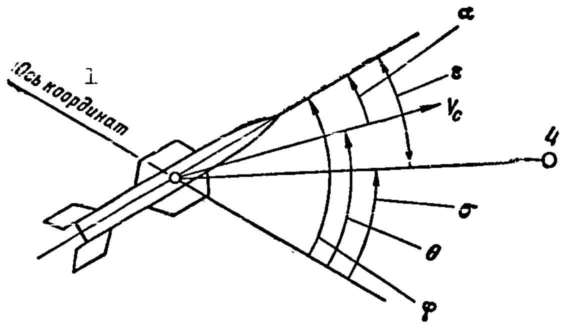

Fig. 41. Angles determining position of missile in space relative to target: α is the angle of attack; ε is the angular homing error; σ is the missile-to-target line angle; θ is the angle of trajectory inclination; φ is the pitch angle. 1) Coordinate axis.

Let us consider typical mutual positions of the missile and the target and establish certain geometrical relationships (Fig. 42). Here we adopt the notation:

STs is the missile (S)-to-target (Ts) line (the sighting line);

θ_{ts} for the angle between the missile-to-target direction and the vector of the target velocity V_{ts};

θ_s is the angle between the missile-to-target direction and the vector of the missile's velocity V_s;

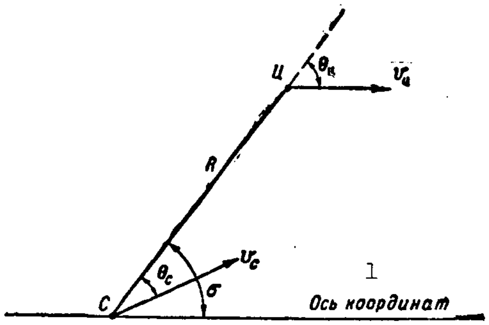

Fig. 42. Geometrical relationships in homing of guided missiles. 1) Coordinate axis.

σ is the angle of the missile-to-target line, which characterizes the position of this line at any specified instant in time relative to the coordinate axes (or the initial position).

Projecting the velocity vectors onto the normal to the missile-to-target direction, we obtain an expression for the angular velocity of rotation of the missile-to-target line:

$$\frac{\partial\sigma}{\partial t}=\frac{V_c \sin\theta_c}{R}-\frac{V_{\text{ц}} \sin\theta_{\text{ц}}}{R}, \qquad (*)$$

where R is the distance between the missile and the target.

It will be seen from this expression that both the parameters of the missile's motion and those of the target's motion influence the angular velocity of the missile-to-target line. The angular velocity at which the missile-to-target line rotates is of great importance for the precision with which the missile is homed onto the target.

As we have already noted, the variation of the missile-to-target direction is embodied in the guidance-system circuit as an individual block known as the <u>kinematic element</u>. The degree to which the kinematic element influences homing of the missile depends on the distance between the missile and the target. At long ranges, both the motion of the target and the motion of the missile exert little influence on the angular velocity at which the missile-to-target line rotates. At short ranges, on the other hand, its influence increases considerably and even slight changes in the motion of the

target or the missile may produce sharp changes in the missile-to-target direction and result in large deflections of the control surfaces, excessive normal accelerations, transients and instability of the missile's flight.

Several methods exist for homing a missile onto its target; each of these has its own characteristic missile-flight trajectory. Inasmuch as the exact expressions characterizing the trajectory of a missile are complicated and depend on many factors, simplified expressions are frequently used to characterize the homing technique; these define the <u>direction</u> of the missile-to-target line and its <u>angular velocity</u> of rotation in space. In analysis of such equations, the distance data are usually not absolutely necessary, assuming that the missile has an effective range adequate for reduction of the target.

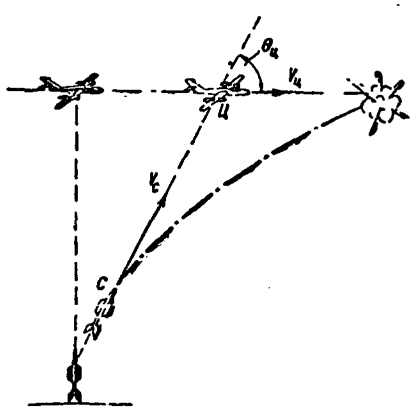

Fig. 43. Technique of homing guided missile on pursuit curve.

We know of five basic methods for homing missiles onto moving targets:

1) pursuit curve homing;

2) pursuit curve homing with constant lead;

3) lead-point homing;

4) the proportional homing technique;

5) the three-point technique.

<u>The pursuit curve homing technique</u> (Fig. 43) is the simplest homing method; here, the missile is always flying directly toward the target, i.e., the missile's flight direction (velocity vector V_s) coincides at any point in time with the missile-to-target direction. This method may be used in automatic-

homing systems in cases where the coordinator aboard the missile is not rigidly mounted and its axis is kept in coincidence with the velocity vector at all times by means of a special device (for example, a weathercock).

Here, the missile's flight trajectory is always curved in the direction of the target's motion and has the shape characteristic for continuous pursuit.

In principle, this technique is reminiscent of the way in which a dog chases a rabbit; thus the literature contains other names for it, such as pursuit-curve or "dog"-curve homing.

The pursuit curve technique for homing a missile may be expressed by the following equations:

$$\theta_0 = 0,$$

$$\frac{\partial \sigma}{\partial t} \neq 0.$$

This means that the homing system will guide the missile directly to the target without any lead whatsoever, and the position of the missile-to-target line in space will change constantly.

Two possible cases must be borne in mind with this technique: pursuit of receding targets (motion on paths in the same direction) and pursuit of approaching targets (on collision courses). In the former case, if the missile has sufficient effective range and a sufficiently high speed, it will inevitably reduce the target. In the latter case, however, the angular velocity at which the missile is turning increases sharply as the distance closes, and at a velocity ratio $V_s/V_{ts} \approx 2$, the required normal acceleration of the missile approaches infinity, even when the target does not maneuver.

This means that on the final segment of pursuit, when the missile has reached its maximum accelerations, a freely maneuvering target may turn aside from the encounter and avoid damage.

Moreover, in view of the large accelerations acting on the missile in sharp turns, large aerodynamic forces are required to guide it, so that the missile must have a large-area wing – an unfavorable feature. Consequently, in spite of its apparent simplicity, this method is virtually never used to intercept unfriendly aerial targets. Basically, it can be used only to guide self-homing bombs.

A particular case of this method may be homing of a missile onto a stationary target, when not only the velocity vector V_s, but even the axis of the missile itself are directed at all times at the target. In this case, the target coordinator has a fixed mount on the missile, and is secured in such a way that its axis will coincide with the missile axis. The missile's trajectory will be a straight line. If with the coordinator set up in this way the missile is homed on a rapidly moving or maneuvering target, it can be established that the velocity vector in this homing method will always be lagging behind the missile-to-target line and, consequently, that the missile will always be directed at a point behind the target. Consequently, this method, which is known as the <u>direct-homing method</u>, is not suitable for moving targets.

<u>The pursuit curve homing technique with constant lead</u> (Fig. 44) consists in flying the missile not straight at the target, but with a certain constant lead δ. In this case the angle between the missile's direction of flight (the vector of the velocity V_s) and the missile-to-target direction has a constant value, and may be expressed by the equation

$$\theta_0 = \delta = \text{const.}$$

The position of the missile-to-target line in space usually changes as well, i.e.,

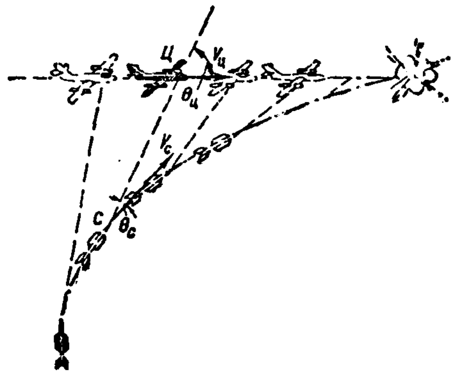

Fig. 44. Method of homing guided missile on pursuit curve with constant lead.

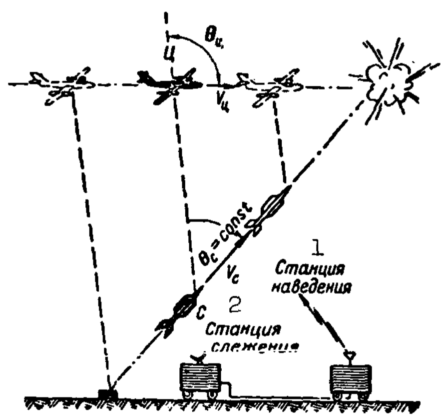

Fig. 45. Method of homing guided missile to lead point. 1) Guidance station; 2) tracking station.

$$\frac{\partial \sigma}{\partial t} \neq 0.$$

In this case, the coordinator aboard the missile must be set up in such a way that its axis will form a constant angle with the missile axis in the direction opposite to the motion of the target.

When this method is used, the missile flies along a trajectory having a smaller curvature, and the terminal segment of its path is almost rectilinear; this does not necessitate large angular acceleration. In this case, favorable conditions for reduction of the target may be obtained with the velocity relationship

$$1 < \frac{V_0}{V_ц} \leqslant 2.$$

given this condition, we may select a lead angle δ that will not cause an infinitely large angular velocity of the missile to arise. But when the necessary angular velocity is larger than that permissible for the missile in question, the missile may "lose" the target and a miss will result.

Cases in which the target changes its direction of flight may be particularly embarassing. Then the lead angle becomes negative and the homing process considerably more complicated, since the missile

must follow the target from the other direction in order to have a positive lead angle as before. As a result, the missile's trajectory will be more complex, the homing time will be much longer, and the firing range will be considerably shorter.

The pursuit curve homing technique with constant lead may also be used in automatic homing systems. Sometimes this method is known as the intersecting-course homing technique.

The lead-point homing technique (Fig. 45) provides for flight of the missile to a computed point of encounter with a moving target along a trajectory on which the missile-to-target line retains a constant direction in space.

If the target does not maneuver and flies in a straight line at a uniform speed, then if the encounter point has been properly computed and if the missile flies at a constant speed, the missile will fly on a straight line with a constant heading to the target (constant lead angle).

The principle of this method may be expressed by the following equations:

$$\frac{\partial \sigma}{\partial t}=0,$$

$$\theta_о=\delta=\mathrm{const.}$$

If the expression for the angular velocity of the missile-to-target line (*) is equated to zero (since in this case $\partial\sigma/\partial t = 0$), we may obtain the law upon which this homing technique is based:

$$V_о \sin\theta_о = V_п \sin\theta_п.$$

From this equation, we may easily obtain the computed lead angle θ_s:

$$\sin\theta_о = \frac{V_п}{V_о}\sin\theta_п.$$

Thus, given a nonmaneuvering target (V_{ts} and θ_{ts} constant), the lead angle remains constant, while the missile-to-target line will displace parallel to its initial position without changing direction (without rotating) in space. In view of this fact, this method is also known as the parallel-approach technique.

In automatic homing systems, this method is implemented by setting up the coordinator on a moving platform that is stabilized by a free gyroscope in such a way that its axis will coincide with the missile-to-target line, and form with the missile's longitudinal axis an angle equal to the computed lead angle. The advantage of this method in homing onto a nonmaneuvering target consists in the negligible normal accelerations that arise when mismatch angles accidentally arise between the coordinator axis and the missile-to-target.

If the missile is homed onto a maneuvering target (V_{ts} and θ_{ts} changing continuously), it is clearly evident that the necessary lead angle will also vary. In this case, therefore, the lead angle may take different values at different moments in time, while the missile's velocity vector will be directed toward a new lead point at each such instant. For this reason, this technique is known in the more general case, i.e., when a missile is being homed onto a maneuvering target, as the technique of homing to an instantaneous leading point of encounter.

In automatic homing systems, this method may be implemented by installing a movable coordinator that makes provision for continuous tracking of the target. This requirement complicates the physical design of the coordinator.

Of all the known homing methods, the method of lead-point homing ensures the smallest g-forces acting on the missile for a given set of firing conditions; even when the target maneuvers, these

forces do not exceed those acting on the target. This makes it possible to have small load-bearing surfaces in the missiles.

In addition to automatic-homing systems, this method may be used in command-type homing systems, as well as when the missile is guided to a lead point on a radar beam in cases where two radars are used with one tracking the target and the other guiding the missile.

The proportional-homing technique (proportional-navigation technique) (Fig. 46) provides for flight of the missile to the point of encounter with a moving target along a path on which the angular velocity of the missile's velocity vector V_s is proportional to the angular velocity of the missile-to-target line. This method makes it possible to take into account the tendency of the missile-to-target line to rotate during the homing process and, in simpler cases, to arrive at an approximation of lead-point homing.

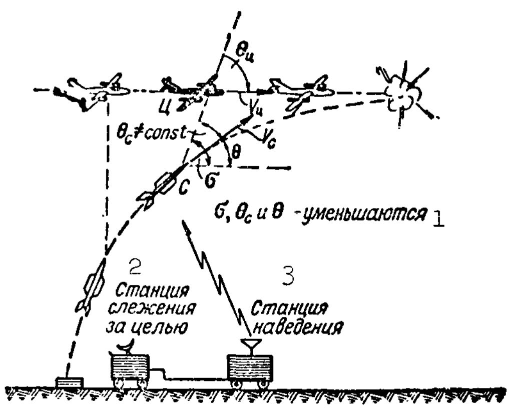

Fig. 46. Technique for proportional homing of guided missile. 1) σ, θ_s and θ diminishing; 2) target-tracking station; 3) guidance station.

The principle of the proportional-homing method may be expressed by the equation

$$\frac{\partial \vartheta_c}{\partial t} = k \frac{\partial \sigma}{\partial t},$$

where k is the navigation constant.

Missiles homed by the proportional-navigation method will tend to strike nonmaneuvering targets colinearly and to tail maneuvering targets without executing steep turns near the target. With this method, the normal accelerations of the missile normally remain within the admissible limits and do not rise to excessive values. This method may be used in both automatic-homing systems and

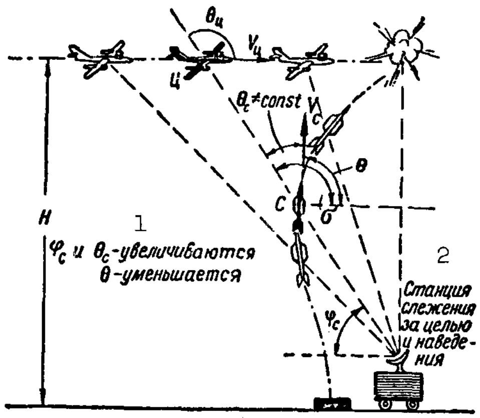

Fig. 47. Homing of guided missile by three-point method. 1) φ_s and θ_s increasing; θ diminishing; 2) target-tracking and homing station.

command systems.

The proportional-homing technique is the most general technique, and one for which all of the foregoing methods are particular cases occurring under simpler conditions.

The three-point method (Fig. 47) provides for flight of the missile to the point of encounter with the target along a curvilinear trajectory on which the missile holds at all times to a straight line connecting the control point with the target. In this case, an observer at the control point will always see the missile between himself and the target. The sighting line connecting the three points – the target, the missile, and the control point – will always be shifting in space to follow the motion of the target.

This homing method may be used for missiles of the ground-to-air (antiaircraft missiles), air-to-ground (winged missiles, guided bombs and torpedoes) and air-to-air classes. In the first case, the control point is stationary and the target moves. In the second case the control point (missile carrier) is moving, while the target may be moving (air-to-sea) or stationary. When missiles are homed onto stationary targets, the homing problem becomes considerably simpler. In homing air-to-air missiles, the fact that the carrier (control point) and target are moving is taken into account. This is the most complex case.

For the case in which the control point is stationary, the principle of the three-point homing method may be expressed by the

following differential equation (for a nonmaneuvering target following a straight-line course at constant speed):

$$\left(\frac{\partial r}{\partial_{\varphi_0}}\right)^2 + r^2 = \left(\frac{V_0}{V_n}\right)^2 H^2 \frac{1}{\sin^4 \varphi_0},$$

where $\underline{r}$ is the instantaneous slant range from the control point to the missile; φ_S is the instantaneous value of the point of missile position from the control point; H is the target height (assumed to be constant).

This method is employed in the case of command and beam-rider guidance systems (along a radar beam). In the latter case (command guidance), the missile is kept on its flight path visually or by means of optical or radar devices.

The advantage of this method lies, in certain cases, in its technological simplicity. For example, in the case of visual control, the responsibilities of the operator are reduced to the superposition of the visible missile image on the image of the target. As a result, the three-point method is sometimes referred to as the coincidence or target-covering method.

The shortcoming of this method is the significant complication of the trajectory in the case of guidance to a maneuvering target, particularly in the case of a moving launch-control site (the "air-to-air" case). However, we can achieve certain simplifications by executing appropriate "maneuvers" of the carrier. For example, given a certain flight trajectory for the carrier, we can achieve a situation in which the lines connecting the control point with the target remain parallel to one another at various instants of time, so that the missile will move along a trajectory of parallel approach. In the case of guidance along a trajectory of this type, the carrier may fly vari-

ous headings, including a heading in the opposite direction.

The calculation of the required missile acceleration shows that in this case acceleration is substantially lower than in certain of the preceding guidance methods; however, at certain sections of the trajectory (for various cases, at various sections) the missile must be adequately maneuverable.

The methods examined here are the basic guidance methods that are characterized by specific flight trajectories for the missile being guided. A portion of these methods are suitable only in homing systems, whereas others are suitable only in remote-control systems (beam-rider guidance, command guidance, television guidance, etc.). Some of these methods may be used both in homing systems as well as in remote-control systems.

These methods may be altered and combined in various ways, and therefore do not exhaust all of the possible cases and versions of missile guidance. The utilization of programming facilities and computer instruments makes it possible to assign any type of trajectory to the missile, i.e., a trajectory that can be executed by the guidance system being employed. As an example of such a derivative method we can cite the method of programmed guidance which is employed in remote-control systems.

<u>The programmed [preset] guidance method (approach)</u> provides for missile flight to the point of target contact along a curvilinear trajectory which satisfies one or simultaneously several unique and assigned requirements such as: the requirement of minimum acceleration, maximum range, minimum flight time, etc.

This method requires separate tracking of target and missile, and this can be carried out in various ways, i.e., optically, by means of heat-sensitive direction-finder equipment, or by means of radar. The

most convenient method is the two-beam radar system consisting of two radar transmitters of which one is employed to track the target and the other to follow the missile. In this case, an angle is formed be-tweeen the two lines of sight, i.e., between the "control point - target" and "control point - missile" lines, and this angle changes during the guidance procedure in accordance with a law which satisfies the set requirements. This angle gradually diminishes and at the instant that the missile comes into contact with the target the angle vanishes. As a result this method is still referred to as the method of angular approach or "the scissor method." [Track-command guidance].

This method is quite flexible and it can be used for various classes of missiles in all possible design versions. This method can be employed, for example, to guide remote-controlled missiles or bombs in such a manner as to provide for minimum deformation of the free-fall trajectory. This method also makes it possible to guide anti-aircraft missiles in such a manner as to provide for maximum flight range. In the latter case, the missile is launched at a great ascent angle in order to enter more quickly the optimum-altitude trajectory and to fly farther in the direction toward the target with the least aerodynamic resistance, thus achieving maximum range. In this case, however, it should not be forgotten that such an initial gain in altitude and the subsequent horizontal flight to the target are not easily reconciled with the requirement of impact accuracy in the final guidance sector.

The method of preset (or free) guidance is the one more commonly employed. In specific cases, when the angle between the lines of sight is constant, we obtain lead-angle guidance, and when this angle is equal to zero, we are dealing with the three-point method.

<u>Combinations of various guidance methods</u> are employed in more complex

cases, in which missiles must destroy targets situated at great distances, or if it becomes necessary to increase the impact accuracy at distant targets. With this guidance method several guidance systems are employed, and the entire flight trajectory of the missile is divided into several sections, beginning with the instant of launch to the instant of target destruction, in accordance with the characteristics of the guidance systems selected.

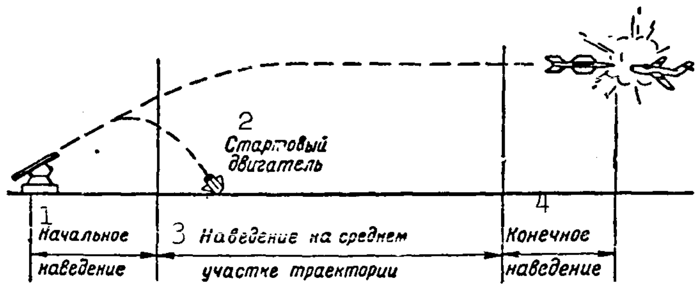

Fig. 48. Missile guidance phases. 1) Initial guidance; 2) booster engine; 3) guidance along middle section of trajectory; 4) final guidance.

This pertains primarily to the "ground-to-ground" medium-range and long-range class of missiles whose flight trajectories are generally divided into three sections (three guidance stages): initial, middle, and final.

In accordance with this, the entire guidance process is divided into three phases (Fig. 48): initial guidance (launch guidance), guidance during middle section of trajectory (middle-course guidance), and final guidance (guidance during the final phase).

The initial-guidance phase is of short duration and encompasses the first portion of the missile's flight trajectory from the instant of launch to the completion of the acceleration period (to the instant of booster separation). The flight trajectory of the missile during this guidance phase is extremely simple — in the majority of cases, a straight line. In this case, striving to simplify guidance problems,

we make every effort to launch the missile so that the guidance system controlling the missile over the middle section of the trajectory can take over the guidance of the missile at the end of the first phase.

The guidance over the middle section of the trajectory is the main and longest lasting guidance phase. The accuracy of guidance at the end of this phase determines the feasibility and need of using a more exacting guidance system in the final phase.

The final-guidance phase encompasses the last section of the missile's flight trajectory and is generally also quite short. Final guidance is employed in those cases in which the accuracy of guidance during the middle section of the trajectory is not sufficiently high to provide for the destruction of the target.

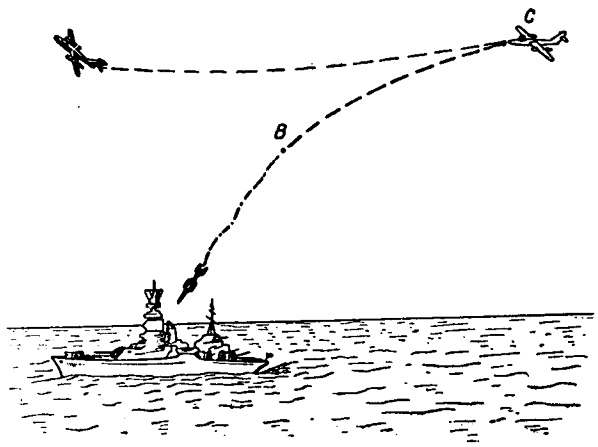

Fig. 49. Flight of guided bomb along free-fall trajectory with self-guidance in final phase: B) Start of self-guidance.

The accuracy of guidance during the middle and final sections of the trajectory is a function of the accuracy of the guidance systems employed in these sections.

Let us examine typical missile flight trajectories during the middle and final guidance phases and let us take note of the main features.

Flight of guided bomb along free-fall trajectory with guidance in final section (Fig. 49). In this case the guided bomb, ejected from a carrier aircraft, flies along a curve that is close to the parabolic until the guidance system takes over. Generally, for purposes of guiding a bomb in the final section, one of the guidance systems is employed, and the guidance method is selected in accordance with the circumstances of the situation - one of those considered above.

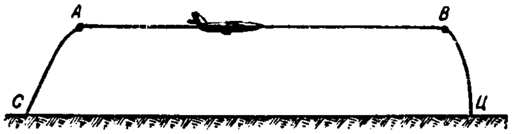

Fig. 50. Flight of an aircraft or a missile along a rectilinear horizontal trajectory: SA) Ascent to preset altitude; AV) powered flight phase at constant altitude; V) instant of engine burnout, with dive to target.

C = S; A = A; B = V; Ц = Ts.

Such guidance is quite simple, since during the first flight phase no guidance system is required; however, this system is inconvenient from the standpoint that the carrier aircraft must approach the vicinity of the target and drop the guided bomb from practically the same distance as would be required in the case of an unguided bomb. After the dropping of a self-guiding bomb (excluding the case in which a semiactive homing system is employed) the aircraft can retreat in any direction.

However, if the bomb is being controlled by a semiactive homing system or by means of a remote-control system (for example, command guidance, television guidance), after dropping its bomb load the aircraft, as a rule, must continue to fly in the vicinity of the target.

Missile flight along a trajectory of specific configuration. The character of the trajectory in these cases is determined by the properties

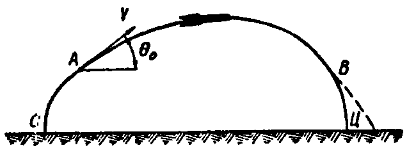

Fig. 51. Flight trajectory of ballistic short-range guided missiles: SA) Powered flight phase; AV) parabolic curve; VTs) parabolic curve with distortion as a result of air resistance.

of the guidance system. Here we can include, for example, the guidance of missiles along a hyperbole or a circle as done in the case of radionavigation guidance systems (see Fig. 90). In this case, after take-off the missile enters the effective zone (range) of the ground radionavigation stations and as a rule flies at constant altitude along a curve that is characteristic of the given guidance system. Upon attaining the area of the target, the missile can either begin its dive to the target or switch over to a regime of final guidance (if such a system is being employed) by means of other systems. In this category we can include the guidance of a missile along a specific curve by means of a magnetometric guidance system.

Fig. 52. Flight trajectory of guided medium-and long-range ballistic missiles: SA) Powered flight phase; ATs) elliptic curve.

Rectilinear horizontal missile flight (Fig. 50). In this case, the missile flies in the region of the target along a straight line at a constant altitude. Such a trajectory is generally selected for the guidance of long-range aircraft or missiles with autonomous guidance systems, as a rule equipped with programming devices. Such a guidance procedure is employed for missiles of the "air-to-ground" and "ground-to-

ground" classes. In the latter case, the missile is launched toward the target at a certain ascent angle, and on attaining the given altitude the missile is switched to a regime of rectilinear horizontal flight. On arrival at the target region, the missile executes a steep dive at the target or it may be guided by means of a self-guidance (homing) system.

The advantage of such a guidance system lies in the fact that the missile flies the shortest possible distance, thus making it possible to achieve the greatest range for the given type of missile.

Missile flight along ballistic trajectories (Figs. 51 and 52). Short-, medium-, and long-range ballistic missiles (rockets) fly along such trajectories.

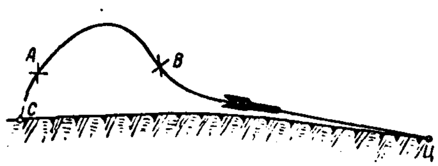

Fig. 53. Flight of winged rockets along ballistic curve, with a flat glide path: SA) Powered flight phase; AV) parabolic curve; VTs) gliding.

Guided ballistic missiles fly along a trajectory determined by the guidance system during the first phase until the theoretical critical point is attained; at this point the missile must have attained a certain velocity and heading, since engine operation ceases beyond this point and the second phase of missile flight begins, i.e., along the theoretical ballistic trajectory.

For a period of several seconds after launch, during the guided phase of the flight, the missile flies upward vertically or at a certain ascent angle, and then on attaining a definite altitude it slowly turns in the given direction until the preset missile-motion parameters are attained at the calculated point; beyond this point, the engine must be shut off.

After engine burnout, the missile continues to climb to maximum altitude (usually, into the rarefied layers of the atmosphere) and then

flies to the target along the descent portion of the ballistic trajectory. On entering the dense layers of the atmosphere, the missile is somewhat decelerated and deflected from the exact theoretical curve.

All elements of the trajectory and the characteristics of missile motion (the coordinates of the end of the active phase, the ascent angle, and maximum missile velocity at this point, determining maximum altitude and missile flight range) are calculated as functions of target position.

In free flight (after engine burnout) short-range missiles (under 300 km) fly along a curve that is close to a parabola, whereas longer-range missiles, including intercontinental missiles, fly along an elliptic curve. A curve of this type represents a portion of an ellipse, one of whose foci is the center of the earth.

The advantage of ballistic missiles lies in the fact that they make possible the achievement of great missile-flight velocities and penetration into the rarefied layers of the atmosphere where air resistance is negligible; this makes possible a substantial reduction in missile flight time to the target, as well as a significant increase in flight range.

Flights of missiles along a ballistic curve, with flat gliding (Fig. 53). Winged rockets fly along such trajectories. The flight of a missile follows a preset programmed curve during the initial phase (initial section of the trajectory), along a ballistic curve in the middle section of the trajectory, and along a free-glide path in the final section, on reentering the dense layers of the atmosphere. This flight path substantially increases the effective range of a winged rocket in comparison to a wingless rocket, given identical reaction-engine characteristics.

Manu-script Page No.	[List of Transliterated Symbols]
107	с = s = snaryad = missile
107	ц = ts = tsel' = target

Chapter 6

HOMING GUIDANCE

§1. INFRARED PASSIVE HOMING GUIDANCE

Of the passive guided-missile homing systems, the infrared system, or a system with a heat seeker, has reached greatest practical significance and widespread acceptance. This can be explained by the numerous advantages that this system exhibits over other systems.

Heat or infrared rays, invisible to the unaided eye, lie in the spectrum of electromagnetic oscillations between the region of visible rays and the ultrashort radio waves in the range of waves from 0.76 to 300 μ (microns). These rays are emitted by all heated bodies. The power of the emitted heat energy is proportional to the fourth power of the absolute temperature. The range of wavelengths in which this radiation of energy takes place, and the wavelength on which the energy maximum is emitted, are both functions of temperature. With a rise in temperature the radiation maximum shifts in the direction of the shorter waves. For example, the maximum radiation from the sun corresponds to a wave of 0.5 μ, while the radiation maximums of jet and piston aircraft engines lie, respectively, in a region of wavelengths between 3 and 4 μ.

In terms of properties, infrared rays differ little from visible light. The basic difference is that the infrared rays pass through various media in different ways. For example, infrared rays pass easily through certain materials that are opaque to visible light (cardboard, black paper, ebonite, etc.), and they are absorbed and scattered to a

lesser extent in the atmosphere. However, the attenuation of any stream of radiation depends on the emission wavelength and the state of the atmosphere. In the case of light haze or fog shortwave infrared rays (λ = 1.5-2 μ) penetrate better and, consequently, exhibit certain advantages over visible rays. In the case of poorer visibility the longer wavelengths (λ = 3-4 μ) are more advantageous. In the case of dense fog, snow, rain, or even in the case of artificial camouflage (smoke screens) the advantages of infrared rays, as compared to visible rays, are almost completely lost.

Not all of the components of the infrared-ray spectrum pass equally well through such materials as, for example, ordinary glass. Therefore, only the shortwave region of infrared radiation, with a wavelength of 0.76 to 2-4 μ, can be employed for the transmission and reception of infrared rays by means of optical systems using lenses and mirrors, thus providing for directivity of emission and reception.

The detection of heat emission is accomplished by means of special receiver units which, among other things, are made up of optical instruments and sensing elements that are designed to react to infrared rays.

For purposes of guiding a missile to a target that radiates heat, the missile is equipped with a "heat seeker" which is oriented to the target and represents, in essence, a heat-sensitive direction finder which continuously determines the position of a detected target with respect to the missile and issues the corresponding commands to the control units. Therefore, it would be more accurate to refer to the infrared homing system as a heat-sensitive direction-finding system.

Heat-sensitive direction finders or heat-sensitive target-oriented devices (Fig. 54) can be executed, from a structural standpoint, in a variety of ways, but they can all be divided into two types: seeker-orientation devices which provide for system operation under regimes

of target seeking and tracking; and simple orientation devices, which are not equipped for automatic target seeking or tracking and make possible only the detection and determination of direction to a target in the field of view of the receiving device.

All heat-sensitive orientation devices are equipped with an optical system which may employ either lenses, mirrors, or a combination of the two. The optical system of the orientation device is installed in the nose of the missile and is covered on the outside by cowling material that permits the passage of infrared rays.

The simplest optical heat-sensitive orientation device (Fig. 55) consist of a lens optical system (an objective) which gathers and focuses the heat radiated by the target; in addition, there is a sensing element that is situated close to the focal plane, and finally there is a modulator that is installed in the focus of the optical system, in front of the sensing element.

The modulator consists of disks which are intended to modulate (interrupt) the stream of radiation from the target in order to make possible their subsequent amplification and the issuance of control signals. For this purpose rasters are applied to the disk. The rasters represent alternating transparent and nontransparent sectors of definite frequency, applied to the disk in the form of a ring. Two rasters with various frequencies are generally applied to each disk. The shape and number of the applied rasters may vary for various systems.

Two modulation disks with two rasters, separated by a narrow raster-free strip, are used in the simplest orientation device. In this case, the heat radiated by the target is received and focused by the objective into a point which strikes the modulation disk that has been made to rotate by a motor; then this focus of radiated heat impinges on the sensing element in which it excites frequency-modulated current

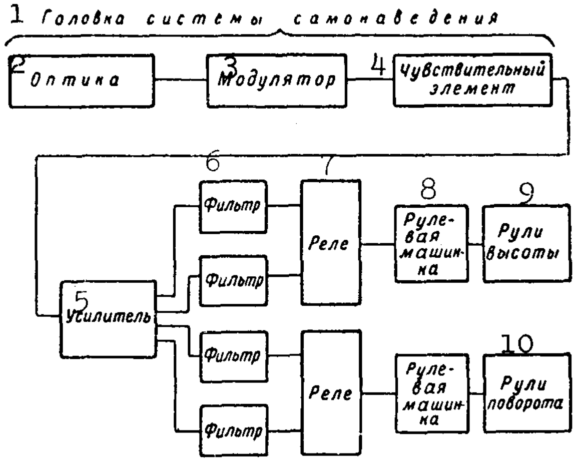

Fig. 54. Block diagram of infrared passive homing system. 1) Head of homing system; 2) optics; 3) modulator; 4) sensing element; 5) amplifier; 6) filter; 7) relay; 8) servomechanism; 9) elevator; 10) rudder.

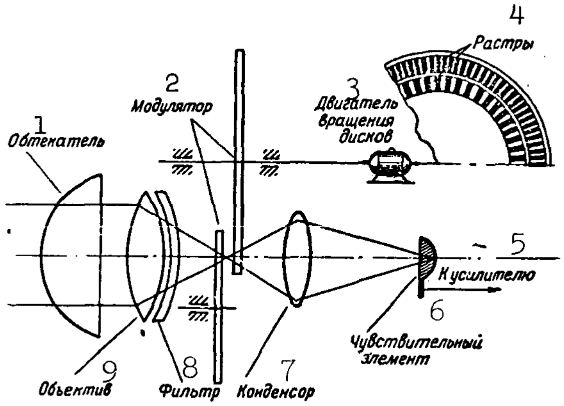

Fig. 55. Diagram of heat-sensitive orientation device. 1) Cowling; 2) modulator; 3) disk-rotation motor; 4) rasters; 5) to amplifier; 6) sensing element; 7) capacitor; 8) filter; 9) objective.

pulses. This signal is amplified and applied to the autopilot to control the missile.

If the target lies exactly along the axis of the orientation

device, the radiation stream will impinge on the sensing element through the raster-free strip of the disk and is not modulated; there will be a voltage balance at the autopilot input and the control surfaces of the missile will be in neutral position. If the target is deflected to the side of the orientation device's axis, the stream will strike the sensing element through the rasters of the modulation disks and be modulated by a certain frequency, depending on the raster of the particular disk through which the stream passed. Two disks are required in order to provide two-channel control: pitch and heading. The disks are set into rotation by a single motor and they rotate synchronously, but they are made so that they modulate the stream alternately. In actual fact, two half-disks are used, and these are mounted in such a manner that the raster-free strips intersect at right angles on the axis of the orientation device. If all of the rasters vary in frequency, the frequency of stream modulation will characterize the direction of target deflection with respect to the axis of the orientation device: to the left, to the right, upward, downward, the autopilot may, in this case, operate on an extremely simple relay circuit. Four filters, tuned to various frequencies corresponding to the raster frequencies of the modulation disks, are mounted at the autopilot output. Relay windings which control the servomotors of the corresponding missile control surfaces are connected to the output of each filter. For the most reliable operation of such a control system, use is made of a switch which with its cam, in sychronization with the rotation of the modulation half-disks, alternately closes the pitch-channel circuits or the heading-channel circuits, thus making the connection for the execution of the appropriate elevator or rudder commands.

It is easy to see that with the utilization of such modulation disks a signal dependent only on the direction of target deflection

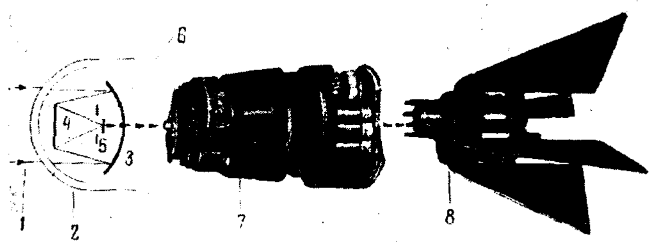

Fig. 56. Basic elements of the infrared homing system: 1) Infrared rays from target; 2) cowling; 3) parabolic mirror; 4) flat mirror; 5) modulator; 6) sensing element; 7) amplifier unit; 8) servomotor and control surfaces.

with respect to the axis of the orientation device appears at the output of the sensing element; this signal is independent of the magnitude of the angle of this deflection. In order to obtain control signals that are proportional to the magnitude of the angle of target deflection, the modulation disks must be more complex.

Seeker orientation devices which can perform under regimes of both seeking and tracking are more complex in design. In the seeking regime, scanning is accomplished in various ways, primarily by rotating a mirror or by shifting the sensing element with respect to the axis of the orientation device. In this case, the instant that the target enters the field of view of the receiving device an electric signal from the sensing element interrupts the seeking regime and switches the drive mechanism of the orientation device to a regime of automatic target tracking. Such orientation devices make possible the determination of the angular velocity of the rotation of the target line-of-sight in space and these devices also make possible the control of the missile in such a manner as to guide it to the target in accordance with the

given guidance method. However, orientation devices of this type are complex in design and rather cumbersome; therefore, simpler versions of these orientation devices are employed in heat-seeker homing heads (Fig. 56), and these may be mounted in a fixed position with respect to the frame of the missile.

In actual practice, the passive heat-seeking homing systems are more complex than the system described. A guided system almost always includes a computer device which provides for this given guidance method, and the autopilot circuit is also more complex.

The effective range of an infrared homing system depends on many factors which cannot be taken into consideration through a simple equation without great difficulty. The tentative effective range $\underline{\underline{D}}$ [Д] may be determined by utilizing the known expression Φ_λ for the stream of infrared radiation which reaches the receiver of the heat-seeking head:

$$\Phi_\lambda = \frac{B_\lambda S_{об} S_{ц} \cos \theta\, \tau_{атм} \tau_{опт}}{Д^2},$$

where B_λ is the energy radiation brightness of the target; S_{ob} is the area of the objective aperture; S_{ts} is the area of the radiation source (target); θ is the angle between the direction to the target and the normal to the radiation surface; τ_{atm} and τ_{opt} are the coefficients by means of which it is possible to take into consideration the absorption and scattering of the infrared radiation by the atmosphere and the optical system of the heat-seeking direction-finder head.

In the case of a jet aircraft the basic radiation source, naturally, is the engine nozzle. In first approximation the integral value of the energy brightness in the direction of the engine axis may be calculated, just as for a gray body, in accordance with the following formula:

$$B_\lambda = \frac{c}{\pi}\left(\frac{T}{100}\right)^4 \varepsilon,$$

where c is the coefficient of the radiation emitted by an absolute black body and is equal to $5.668 \cdot 10^{-4}$ w/cm$^2 \cdot$deg^4; ε is the emissivity; T is the temperature of the radiator, in degrees Kelvin.

Apparently, a necessary condition for the detection of a target is a sufficiently great excess between the incoming stream of radiation Φ from the target and the minimum required radiation stream Φ_{por} which is determined by the threshold of receiver sensitivity.

As a result, we obtain a theoretical formula for the effective range of the heat-seeking head:

$$Д = \sqrt{\frac{c}{\pi}\left(\frac{T}{100}\right)^4 \varepsilon \frac{S_{ц6} S_{u} \cos i \, \tau_{атм} \tau_{опт}}{\Phi_{пор}}}.$$

In this case it is necessary to take into consideration the following circumstances. There exist three unique physical properties which cause the attenuation of the infrared radiation by the atmosphere: absorption by the molecules of gases which make up the atmosphere; scattering by particles of haze as well as by particles making up fog and clouds; and scattering by molecules of atmospheric gases. Thus it becomes quite clear that the quantity τ_{atm} is not uniquely defined and is a function of meteorological conditions, height above sea level, distance to target, etc. Estimates of the transparency of the atmosphere under various conditions are presented in the appropriate handbooks.

The quantity Φ_{por}, substituted into this formula, must correspond to the threshold sensitivity of the receiver being employed to the given type of radiation or, in other words, it is necessary to take into consideration the spectral composition of the radiation and the characteristic of the spectral sensitivity of the radiation receiver.

Thermocouples, bolometers, photocells, and photoresistors can be used as the sensing elements in a heat-sensitive direction finder that produces the electrical control signal upon the incidence of infrared rays on its "working surface." Thermocouples and bolometers have the advantage that they react identically to the radiation of almost all wavelengths in the infrared band and make possible the utilization of these wavelengths for the detection of targets that are only slightly hotter than the temperature of the surrounding background. But since the operation of these devices is based on the heating of the sensing elements, they exhibit great lag (0.01-0.02 sec) and cannot be used for the detection of fast-moving targets.

Photoresistors are the best sensing elements for the latest types of heat-sensitive direction finders; these devices operate on the basis of the phenomenon of photoconductivity in semiconductors (the photoconductive effect). These infrared-radiation receivers are made in the form of a thin high-resistance film (above 100,000 ohms). The photoeffect is produced upon the incidence of infrared rays on the film, and free electrons appear in the film layer; the resistance of the sensing element changes (drops), and this leads to a change in the voltage on the film, if it is connected into the power line. Such photoresistors exhibit virtually no lag below a certain modulation frequency (the reaction time ranges from several microseconds to several milliseconds).

The photoresistors are made of various materials. Depending on the material employed, the photoresistors exhibit the maximum sensitivity only within a definite frequency range. For example, lead sulfide photoresistors are best able to receive radiation on a wavelength of the order of 3 μ; photoresistors of lead telluride are sensitive to radiation on a wavelength of 4.5 μ; photoresistors made of lead selenide

are sensitive to radiation on a wavelength of 6 μ; photoresistors made of indium and antimonide are sensitive to radiation on a wavelength of 7 μ; germanium photoresistors are sensitive to radiation on extremely great wavelengths (approximately to 100 μ). In order to impart infrared sensitivity to these materials, they must be subjected to special treatment, subsequent to which their sensitivity attains an order of magnitude of 10^{-10} w and higher.

This sensitivity for all of the photoresistors, with the exception of the lead-sulfide and, possibly, the lead-selenide, resistor is achieved by artificial cooling to a temperature of the order of minus 70° (usually, by means of dry ice), and this complicates the use of these photoresistors. It has been reported that the sensitivity of the latest lead-sulfide elements is such that when using a mirror having a diameter of 7.5 cm it becomes possible to detect heat radiation from a conventional two-kilowatt electric furnace at a distance of about 16 km. In this connection, we know that the radiation power of a contemporary aircraft is generally higher than two kilowatts, and the radiation power of an ocean-going vessel is expressed in many tens and even hundreds of kilowatts.

Extremely sensitive and fast-reaction superconductive bolometers of niobium nitride cooled with liquid hydrogen have been constructed abroad with semiconductor materials. These bolometers, in addition to their high integral sensitivity, exhibit a wide spectral characteristic (up to 10 μ), and this makes possible their utilization for purposes of detecting radiation from bodies heated only slightly; furthermore, it becomes possible to increase the effective range of the heat-seeking direction-finding systems. In this connection, there arises the problem of developing and producing special forms of glass for use as cowling material, since conventional glass is transparent to all radiation on

wavelengths below 3 μ.

The cowlings for infrared homing systems (Fig. 57) are made of material that is extremely transparent to the infrared radiation of that section of the spectrum in which the homing system functions. Moreover, the cowling must be strong and capable of withstanding high temperatures. According to data from abroad, no material has as yet been developed that can satisfactorily meet all of these requirements fully. For example, a material made of arsenic trisulfide (trade name "servofaks [sic]") passes approximately 70% of the infrared energy in the range of wavelengths from 1.5 to 10 μ. The transparency of this material may be increased to 90-95% in a narrow sector of the spectrum by using a special coating which is used for this same purpose in optical lenses. However, it has been shown that this material cannot function satisfactorily for any length of time at temperatures higher than 150°.

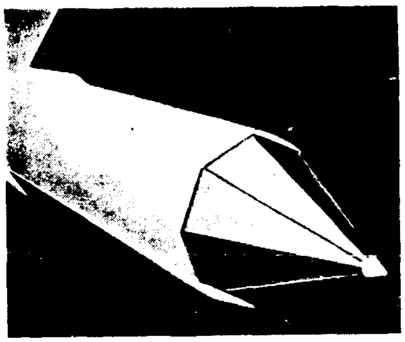

Fig. 57. External view of optical cowling on the British "Firestreak," a guided missile of the "air-to-air" class.

In addition to these data, there have been references in the press to the effect that cesium arsenide glass has been developed abroad, and that this glass is transparent to infrared rays with wavelengths to 12 μ; selenium arsenide glass, transparent to infrared radiation with wavelengths up to 21 μ has also been developed.

We know of about 20 various materials which can be used as cowlings for infrared homing systems, but each of these has its own shortcomings, in addition to the above-mentioned advantages.

The selection of material for the optical cowlings depends on the

sector of the spectrum and the passband of the system, as well as on the specific ambient conditions under which the system must operate.

In addition to the heat-seeking homing heads, noncontact optical detonators using the infrared radiation from the target have been developed to inflict damage on a target even in the case of a failure to achieve a direct hit, i.e., the missile passes close to the target. Missiles employing any homing and guidance systems can be equipped with such noncontact optical detonators.

The basic advantage of the heat-seeking direction-finder systems employing the infrared radiation from the target lies in their high resolving power. Their resolving power is substantially higher than in the case of radar systems. For example, a radar unit operating on a wavelength of 8 mm, given a reflector diameter of 30 cm, can distinguish targets separated by 400 m at a distance of 8 km. The heat-seeking direction finder, with a reflector diameter of only 7.5 cm, can distinguish the engines of individual aircraft at a distance of 8 km. Another advantage of the infrared system is the fact that it does not emit any signals on its own, thus providing great operational cover and security.

As has already been indicated, the effective range of the heat-seeker heads in homing systems depends on the temperature and the area of the target's radiation surface, the sensitivity of the receiving device in the head, as well as the state of the atmosphere and the time of day. The fact that the system works well at night, but not nearly as well during the day, represents a significant defect. The range of such systems is also limited by the effect of natural interference such as the background radiation of the night sky, clouds, near-by structures, water surfaces, etc. To eliminate this defect, methods have been developed to compensate the effect of this form of

radiation.

With respect to artificial interference, the heat-seeking systems are more stable and less subject to the effect of this artificial interference than are radar systems; however, the possibility of interference is not excluded. These systems may encounter interference as a result of artificial sources of heat – so-called false targets – which may, for example, be produced by infrared projectors. This type of interference may deflect a missile from the proper course. There are references in the literature to the effect that there is no possibility at the present time of designing a system that would be capable of distinguishing with sufficient accuracy the difference between true and false targets that have similar characteristics.

The heat-seeking homing heads guide the missile to the target with the extremely great accuracy that is characteristic of all homing systems. Both for passive and active as well as semiactive homing systems, guidance errors diminish with distance from the point of missile launch, i.e., with approach of missile to target. However, in the case of violent target maneuvering, in which case excessive lateral missile acceleration may result, as well as in the case of the appearance of transient responses in the autopilot, even these guidance systems may fail to provide a direct hit against the target.

Infrared passive homing systems may be used for missiles of the following classes: "ground-to-air," air-to-air," and air-to-ground." For missiles of the class "ground-to-ground" they may be used in combination with other guidance systems.

The opinion has been expressed in the foreign press that the infrared system may prove to be extremely valuable for purposes of intercepting a supersonic ballistic guided missile whose basic structural elements are made of plastic. If it eventually becomes possible

to design new homing systems involving the phenomenon of heat radiation produced by surface friction betweeen supersonic missiles and the atmosphere, or if it becomes possible to receive a sufficiently powerful signal from the heat produced by the exhaust gases of a guided missile or an enemy aircraft, the heat-seeking heads will be of inestimable value.

§2. ACTIVE (RADAR) HOMING SYSTEM

For active homing systems it is characteristic that the missile itself irradiate the target by means of its on-board energy source, and the signals reflected from the target are received by the missile's receiver and are transmitted to the autopilot input for purposes of controlling the self-guiding missile.

Among the active homing systems, only the "radar" system has found practical application. Other active systems are not of practical importance because of production difficulties, or a number of other serious limitations, including the negligibly small effective range.

The active radar homing system includes a transmitter, a receiver, an antenna device that is used jointly for transmission and reception of signals, a computer device, and such other equipment as is necessary for the working out of the control signals and the distribution of these signals through the appropriate control channels.

The active radar homing system is similar in structure to a conventional automatic target-tracking radar station, except for the fact that the obtained control signals in a radar station are applied to the motors which set the antenna system into rotation so that it constantly follows the target, whereas in the case of the homing system the control signals also pass through the autopilot to the various servomechanisms of the missile. Consequently, there is only a single closed loop in a radar station – the angular-coordinate target-tracking

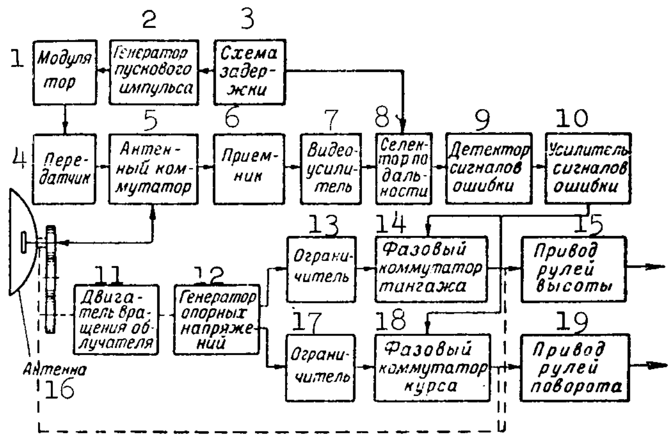

Fig. 58. Block diagram of active (radar) homing system. 1) Modulator; 2) trigger pulse generator; 3) delay circuit; 4) transmitter; 5) antenna switch; 6) receiver; 7) video-amplifier; 8) range selector; 9) error-signal detector; 10) error-signal amplifier; 11) motor by means of which the primary radiating element is set into motion; 12) reference voltage generator; 13) limiter; 14) pitch phase commutator; 15) elevator drive; 16) antenna; 17) limiter; 18) heading phase commutator; 19) rudder drive.

loop; however, in a homing system there are two closed loops – an angular-coordinate target-tracking loop and a missile-control loop (Fig. 58).

In the radar homing system the target orientation device functions in the role of the angular-coordinate target-tracking loop, and this device determines automatically the position of the target with respect to the missile and works out the command signals that are necessary to control the missile.

Radar orientation devices operate on the principle of automatic target tracking with respect to angular coordinates, and this involves the following. The antenna of the orientation device, just like the antenna of a radar station, automatically turns to track a moving target

so that the axis of the antenna seeks constantly to coincide exactly with the direction to the target. This is achieved by the conic sweep of the radio beam formed by the antenna. The narrow cigar-shaped beam, slightly deflected with respect to the central (optical) axis of the antenna, rotates about this axis in space and describes a conic surface along whose axial cross section the radiation intensity changes according to a special law (Fig. 59). The radiated power is less than maximum and amounts approximately to 0.7-0.8 of the maximum along the central axis of the antenna, and with distance from this axis in any radial direction the radiated power increases to its maximum on the generatrix of the cone described by the axis of the rotating beam, and then again diminishes. Thus in its rotation the beam describes a conic surface with a depression in the center.

This radiation pattern is obtained by the rotation of the vibrator, shifted with respect to the optical axis of the antenna, which coincides with the axis of the fixed parabolic reflector, or by the rotation of the reflector, inclined with respect to the fixed vibrator positioned on the optical axis of the antenna.

The intensity of radiation along the central axis of the antenna will be identical for all positions of the rotating beam. Therefore, this axis is referred to as the equal-signal line.

If the central axis of the rotating beam is directed exactly toward the target, i.e., when the target is in the equal-signal zone of the beam, the energy reflected back by the target to the receiver will, in first approximation, be identical for all angular positions of the beam during its rotation and the intensity of the received signal will prove to be constant (Fig. 60). As soon as the target begins to move away from the central axis of the antenna (see Fig. 59), the received signal will no longer be identical in amplitude; the amplitude of the

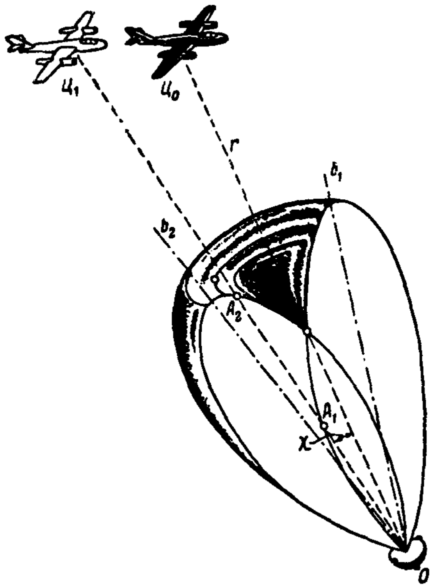

Fig. 59. Cross section of radiation pattern produced by the rotation of a radar beam about the central (optical) antenna axis: Or) Optical antenna axis and equal-signal line of radiation pattern; v_1 and v_2) direction of maximum radiation intensity for two positions of rotating beam; Ts_0) target in equal-signal zone; Ts_1) target outside of equal-signal zone.

в = v; Ц = Ts

signal will attain its maximum at those instants in which the beam maximum moves close to the target line (point A_2), and the beam amplitude will attain its minimum in those instants after which the beam moves away from the target line (point A_1). The change in pulse amplitude – signal modulation – follows a periodic law close to the sinusoidal (Fig. 61), and here the frequency of amplitude change is equal to the axial-rotation frequency of the antenna beam. The speed of beam-axis rotation is generally assumed to be 30-60, and sometimes 100 and more, revolutions per second.

It is clear that the pulse percentage modulation will be all the greater, the larger the angle between the axis of the antenna and the target line; consequently, amplitude modulation of the signal is a measure of the angular distance between the moving target and the axis of the antenna. The phase of the reflected-pulse amplitude envelope will be a function of the direction in which the target shifted with respect to the axis of the antenna.

There will be video pulses at the output of the receiver whose voltage will change according to the same function as that which governs the change in radio pulse amplitude at the receiver input. After detec-

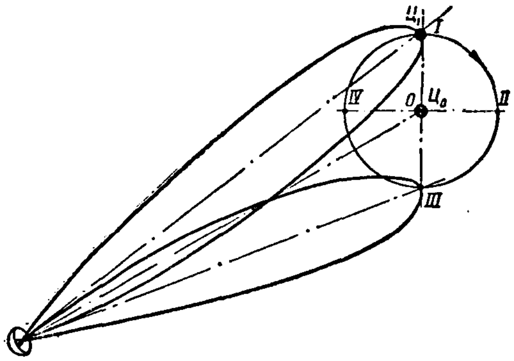

Fig. 60. Position of rotating beam during period of rotation with respect to two various target positions: I, II, III, and IV) Positions of beam during rotation periods; Ts_0) target in equal-signal zone; Ts_1) target outside of and above equal-signal zone.

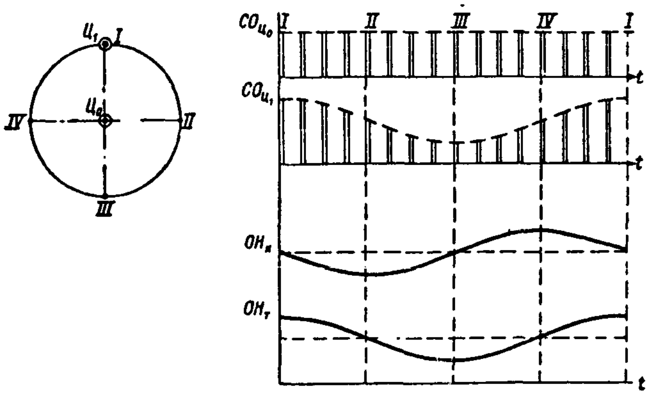

Fig. 61. Nature of change in video pulse (error signal) envelope for two various target positions and change in reference voltages during period of beam rotation: SO_{ts0}) Error signal during period, for target Ts_0; SO_{ts1}) error signal during period, for target Ts_0; SO_{ts1}) error signal during period, for target Ts_1; ON_k) reference voltage of heading channel; ON_t) reference voltage of pitch channel.

CO = SO; OH = ON

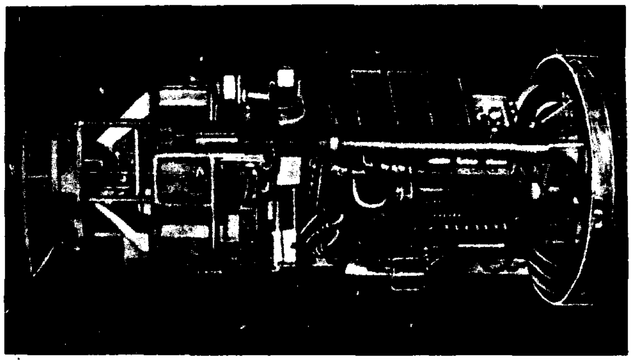

Fig. 62. External view of the radar homing head of a guided missile.

tion, a variable voltage is obtained from these video pulses, and the frequency of this variable voltage is equal to the frequency of antenna-beam rotation, with the amplitude and phase determined by the magnitude and direction of the angular shift of the target with respect to the axis of the antenna. This voltage is referred to as the error-signal voltage. After amplification this voltage is applied to the control-signal shaping unit. The basic elements of this unit are the phase commutators to which, in addition to the error-signal voltages, are applied the reference voltages which represent two sinusoidal voltages whose frequencies are equal to the frequency of beam rotation, and the phases are shifted by 90° with respect to one another. Reference voltages are obtained from a two-phase a.c. generator whose rotor is seated on the axis of antenna rotation. The phases of these voltages are coupled strictly to two missile-control channels: heading and pitch.

Phase commutators, sometimes referred to as phase detectors, yield rectified d.c. voltages at the output. A constant voltage whose sign is a function of the direction in which the target shifts from the central axis of the antenna in the horizontal plane (with respect to the azimuth) is applied to the output of the heading commutator; the

magnitude of the voltage is determined by the magnitude of this shift. A voltage whose sign is a function of the direction in which the target shifts from the antenna axis in the vertical plane (with respect to elevation) is applied to the output of the pitch commutator; the voltage magnitude will be determined by the magnitude of this shift.

The voltages from the commutator outputs, after appropriate amplification, are applied to the heading and pitch antenna-drive motors which turn the antenna in the horizontal or vertical plane, respectively, until the deflection of the target from the central axis of the antenna has been overcome, i.e., until the error signal disappears.

This is how the target-tracking circuit of the radar homing system works.

The on-board missile-control circuit which includes the autopilot and the control units differs in no significant way from standard circuits. Control is carried out over two channels: heading and pitch; the roll channel is generally employed to stabilize the missile.

The control signals applied to the autopilot come from the output of the computer device which converts the information it receives in accordance with the guidance method being employed. Depending on the selected method, data on the angular shifting of the target, and sometimes data on the angular velocities of these shifts, must be fed to the computer device. This information may either be obtained directly from the antenna which is constantly tracking the target and whose position with respect to the missile is constantly changing, or from the same control-signal shaping unit (the control unit).

The latter source of information regarding the motion of a target could be the only such unit, if the axis of the antenna were rigidly coupled with the frame of the missile. In this case the output voltages of the control unit would be applied to the autopilot and would be used

directly for purposes of controlling the rudder and elevators. However, rigid coupling of the antenna to the missile frame is virtually never used. This can be explained by the fact that in the case of rigid antenna fastening, given random missile oscillations or given the loss of the target by the tracking system as a result of violent target maneuvering at short distances, the target may pass beyond the field of view of the radar unit, thus causing the missile to lose the target. In order to prevent this, the antenna system of the orientation device is mounted on a stabilized platform and may, within certain limits, turn rapidly to follow the target, while the missile is in a position to execute slower turns.

If the missile executes certain evolutions in accordance with the given guidance method, the antenna must also react to these changes in missile position in space, turning sufficiently in the opposite direction to remain directed at the target. In this case the angular velocity of antenna rotation with respect to the missile and the angular velocity of missile rotation in space can be measured and the angular velocity of the target line-of-sight in space can be easily computed. This makes it possible to use any of the known guidance methods that are suitable for homing systems.

As has already been pointed out the radar orientation device carries out the automatic tracking of the target on the basis of the angular coordinates. Measurement of range is not necessary for the operation of the homing system; however, the automatic tracking of the target with respect to range is useful in many cases. First of all, range may be employed in computer devices for the solution of the encounter problem in certain guidance methods. Secondly, if there are many targets or extraneous objects in the field of view of the orientation device, it becomes necessary from the standpoint of guiding a

missile to a specific target to "select" the chosen target. This is accomplished by means of automatic target tracking with respect to range, or in other words, strobing. For this purpose a selector is introduced into the system; this selector develops a strobe pulse which permits the passage into the receiver channel only of the narrow range sector (of the entire irradiated space) in which the desired target is situated; thus the possibility of other targets entering the signal system is excluded. This increases the operational reliability of the homing system.

For purposes of guiding a missile to a desired target it is, first of all, necessary to lock onto the target both with respect to the angular coordinate and with respect to range. For this purpose the target orientation device may initially be permitted to function in an angular-coordinate seeking regime, turning the antenna system through given angles, thus scanning a definite sector of space. At the same time, or after locking onto the target with respect to the angular coordinates, the target is automatically sought with respect to range until the required target is "locked on" with respect to range.

After the target has been "locked on" with respect to all coordinates, the angle error signals required for missile control will now be worked out in accordance with the "selected" target.

There are a number of ways in which the missile orientation device can select or lock on to the target, and this includes selection according to special target designations by means of auxiliary facilities. For example, prior to the launching of "air-to-air" missiles equipped with active radar homing systems, target detection and selection may be carried out in the following ways:

1) by the radar orientation device of the missile;

2) with the optical instruments carried on board the carrier air-

craft;

3) by means of the fire-control radar unit of the carrier aircraft.

In the first case, the information from the orientation device of the missile may be indicated on a special dial which the pilot can scan and by means of which he can determine whether or not the desired target has been "selected." In the second case, the antenna of the missile's orientation device pairs with the optical aiming sight of the aircraft and is controlled by the latter. The correctness of target selection is verified by the pilot. In the third case, the orientation device of the missile is paired with the radar unit aboard the aircraft, and this unit exhibits both great power and great antenna dimensions, thus providing for greater detection range than either the radar unit in a missile or the optical system of an aircraft. Using the data provided by the aircraft radar unit, the pilot guides the aircraft to the detected target. In order to confirm the fact that the orientation device of the missile has "selected" the desired target, a comparison of the "selected" orientation-device signal with the signal from the radar unit in the aircraft is carried out. As soon as the desired target has been "selected," the missile is launched.

The required accuracy of direction, which must be imparted to the missile at the time of launch, is determined by the tactical-technical specifications of the missile: the angle of the missile's radar antenna turn, the beam width of this radar unit, the anticipated deviation during launch, the maneuverability of the missile, etc.

In the case of "air-to-ground" missiles, target detection in the majority of cases is accomplished by means of the fire-control radar unit of the carrier aircraft. Prior to launching missiles of the class "ground-to-air" it is also necessary for the antenna of the missile's orientation device, in the seeking regime, to be matched to the an-

tennas of ground or sea-going vessel radar units employed for the tracking of detected targets.

Active radar homing systems may theoretically be employed for missiles of all basic classes: "air-to-air," "air-to-ground," "ground-to-air," and "ground-to-ground." For missiles of the class "air-to-ground" and "ground-to-ground," these homing systems may be used when there is sufficient radar contrast offered by the target with respect to the surrounding background, i.e., primarily for missiles of the subclasses "air-to-vessel," "vessel-to-vessel."

Active systems are rarely used, particularly for missiles of the class "ground-to-ground"; but in principle they may be used both for short-range missiles (basically for the subclasses "ground-to-vessel" and "vessel-to-vessel"), as well as for long-range missiles. In the case of short distances, the missile in essence becomes an "air-to-ground" missile after launch. In the case of long-range missiles active homing may be employed for the final guidance phase. In this case, the orientation device of the missile, during the final guidance phase, must initially function in a seeking regime, and after selection of the target this unit must function in a tracking regime. The requirements imposed on the radar orientation device of the missile must be matched to the accuracy of the guidance system during the approach phase.

In actual practice, active radar homing systems are used on a widespread scale for missiles of the class "air-to-air." In this case, we have the positive factor that after the launching of a missile with such a system, the carrier aircraft may fly off in any direction or launch a second missile. The number of targets which can be attacked, or the number of missiles that can be launched against a single target, depends on the time of detection and the time of target selection by

the radar unit of the carrier aircraft, and it is also a function of the time of detection and selection of this target by the orientation device of the missile; these numbers are also functions of the time required to launch a missile, the velocities of the carrier aircraft and the target, the number of missiles aboard the carrier aircraft, and the possibility of mutual radar interference caused by all of the operating radar units (both of the missiles and of the carrier aircraft). The effect of mutual interference may be reduced or eliminated by dispersing the carrier frequencies of the radar units in the missiles and aboard the carrier aircraft.

A shortcoming of the active radar homing system is its limited effective range, although this range may exceed that of the passive infrared system.

The effective range of the active radar homing system could, in principle, be sufficiently great, but it is actually restricted by the increase in the weight and the dimensions of the on-board equipment required in the missile. The presence in the missile of a transmitter substantially increases the weight of the system and the power sources.

The maximum effective range of the active homing system, characterized by the range of the automatic tracking system, may be determined in accordance with the following formula:

$$Д_{ао}=\sqrt[4]{\frac{P_{изл}\,\eta^2 G^2 S_{ц}\lambda^2}{64\pi^3 P_{min}}}$$

or, expressing G in terms of the antenna-reflector diameter,

$$Д_{ао}=\sqrt[4]{\frac{P_{изл}\,\eta^2 \pi D^4 S_{ц}}{64\lambda^2 P_{min}}},$$

where $\underline{D}_{as}$ is the effective range of the active homing system; P_{izl} is the radiation power of the missile's transmitter; η is the coefficient

by means of which we characterize the level of intersection between the directivity pattern and the optical axis of the antenna (approximately 0.7-0.8); G is the antenna gain factor; D is the diameter of the antenna; S_{ts} is the effective area of the target; λ is the wavelength; P_{min} is the threshold sensitivity of the receiver.

We can see from the formula that in order to increase the effective range of the active homing system it is necessary to increase the diameter of the antenna and the power of the transmitter; however, the possibility of carrying these steps out in a missile are seriously hampered by the permissible dimensions and weight of the equipment. The threshold sensitivity of the receiver is also restricted by the noise of the radar receiver. Hence it follows that the effective range of active radar homing systems cannot be made sufficiently great. This is a serious shortcoming of this system and limits its application.

In order to achieve the maximum reduction in the weight and dimensions of the active homing system (primarily, of the antenna system), it would be advisable to employ equipment operating on a band of shorter wavelengths. However, the method of shortening the wavelengths may be employed only up to a certain limit, since the reduction in wavelength generally carries with it a drop in the maximum possible transmitter power and impairs the threshold sensitivity of the receiver.

The resolving power of the system is also a function of the wave band and governs the separation of targets situated close to one another as well as the accuracy of determing the direction to the target, which characterizes the accuracy of the guidance system. Although the resolving power and the accuracy of determining the direction to the target are determined primarily by the width of the beam and the flare of the resulting radiation pattern (the conic angle described by the axis of

the beam), a narrower beam can be achieved without increasing the dimensions of the reflector by employing shorter wavelengths. The flare angle of the pattern, in such cases, is generally assumed to be equal to or less than twice the width of the beam.

The accuracy of the active guidance system, excluding the factors that are common to all of these systems (target characteristics, the characteristics of the autopilot, the aerodynamic characteristics, the guidance method, etc.), is determined primarily by the range of wavelengths and the antenna characteristics; furthermore, as in any homing system, the guidance accuracy increases as the distance between the missile and the target diminishes.

A significant shortcoming of the active radar homing system, as in all radar guidance systems, is the ability of the enemy to generate interference: by using special stations to interfere with the active systems, and by the ejection of metal-coated strips and dipoles to interfere with the passive systems. To increase the ability of such systems to overcome interference, the coding of transmitter radio signals is resorted to, with the subsequent decoding of the signals received from the target in the radar receiver. In addition, use is made of certain special devices which can identify and reject the interference signals produced by the metal-coated strips (selection of moving targets, etc.).

An advantage of this and all other radar systems is their little dependence on meteorological conditions.

All radar homing systems (active and semiactive) call for the installation of special radar cowlings, exhibiting satisfactory aerodynamic and electrical characteristics, in the nose of the missile to cover the orientation devices of these guidance systems.

The cowlings used for the radar orientation devices of the missile

are made of high-quality dielectrics and are pointed and well streamlined.

From the standpoint of least radar-beam distortion the best cowling shape is one that is spherical (Fig. 63). The waves from the radiation center impinge normally on the dielectric in such a cowling (at right angles) regardless of the position of the scanning antenna, and this produces no beam refraction. Although other waves farther removed from the center of the beam impinge on the cowling at other angles, any distortion which may result will be identical regardless of antenna position. However, at high velocities a cowling shape of this sort will not be satisfactory from the standpoint of aerodynamics. Therefore, with increasing missile flight velocities, the degree of cowling "softness" must be increased, although this may result in the introduction of certain distortions in the shape of the radar beam, and this has an effect on guidance accuracy.

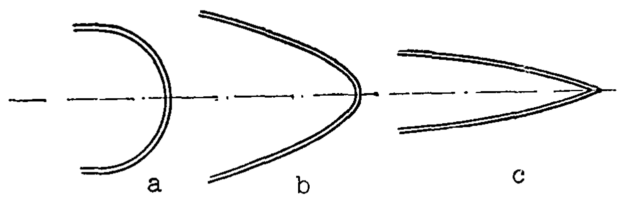

Fig. 63. Possible cowling shapes for the antennas of guided-missile radar homing systems: a) Spherical; b) streamlined; c) pointed.

As the shape of the cowling becomes more pointed, the problem of achieving the least distortion of the beam becomes more difficult. In this case, the angle of radiowave incidence on the cowling changes rapidly as the angle of antenna turn changes, and if the cowling has been put together from dielectric sheets of identical thickness, the degree of radiowave reflections and absorptions will change as the angle of antenna turn changes, with the distortion in the direction of

the beam perhaps not identical to the degree of antenna turn for the various angles of deflection from the central axis. Therefore, in the construction of pointed cowlings dielectrics that are not of identical thickness are selected and these are generally not of the same material but rather of a combination of various materials exhibiting a variety of electrical characteristics.

Radar cowlings are characterized by a number of electrical characteristics such as the transmission factor, reflectance, the refractive index, etc., which exert influence on missile control and sometimes reduce both accuracy and reliability of guidance.

The transmission factor is the ratio of the transmission power to the incidence power and is never equal to unity for actual cowling materials. However, since the effective range of the radar unit is proportional to the fourth root of the transmitted power, it exerts no significant effect on a reduction in range. Therefore the path of impairing the transmission factor of the cowling somewhat is generally taken in order to achieve some improvement in the remaining characteristics.

In the majority of cowling designs the magnitude of reflection is a function of the angle of incidence as well as of the polarization of the waves of radiated and received electromagnetic energy. This makes it difficult to obtain minimum reflection, since the angle of incidence and the direction of the polarization vector may change within a wide range.

Multiple reflection within the cowling and in its walls may increase the level of the minor lobes and shift the radar beam.

If the cowling and the antenna vibrate in relation to one another, there may be a significant increase in the level of microphone noise in the radar unit, as a result of which the signal that is reflected

from the target may be masked. Therefore, the cowling is designed and built with particular care.

Beam refraction in the cowling sometimes yields false data regarding the position of the target, and may also produce errors in the measurement of angular velocity. The magnitude of the refractive index of the beam, changing as a function of the angle of antenna rotation, may exert a significant effect on missile control. In this case, the commands trasmitted to the missile control system will be erroneous and the missile may execute incorrect maneuvers. Because of the asymmetry of the effects of polarization with respect to the cowling, the refractive index in the vertical plane will differ from the refractive index in the horizontal plane. This makes it difficult to make control systems and cowlings which can provide for normal missile guidance.

A reduction in these losses and distortions is achieved in contemporary cowling design by using cowlings with thin walls, laminated walls, or with a wall whose thickness is equal to half the wavelength. A cowling with laminated walls consists of two very thin layers of dense material (for example, fiberglas, soaked in tar), and separated by a low-density medium. This medium may be air, cellular fiberglas, paper, or foam plastic. To eliminate the shifting of the sighting line, a cowling with an inner (middle) layer of foam plastic is used. In this case, the cowling thickness is generally made to diminish gradually as a function of the angle of radar-beam incidence.

The latest models of missiles using radar homing systems ("Falcon") employ ceramic cowlings whose characteristics depend only slightly on the heating temperature.

§3. SEMIACTIVE RADAR HOMING SYSTEM

Of the semiactive homing systems the radar system has found prac-

tical application. In this system the radar transmitter which irradiates the target is not mounted in the missile but at some outside command post.

For reliable missile guidance to the target the target must constantly be irradiated by electromagnetic energy, i.e., the antenna of the radio transmitter must always be directed at the target and in the case of a moving target the antenna must always follow after the target. Therefore, a radar unit with an automatic target-tracking device is always used as the outside transmitter. The principle of operation in such a radar unit differs in no way whatever from the operating principle of the radar unit employed in active homing systems, with the exception of the difference in the point of installation.

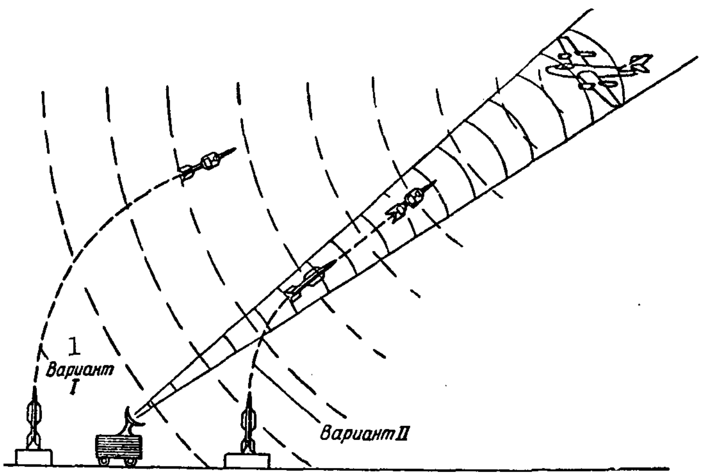

Fig. 64. Two possible versions of a semiactive homing system. 1) Version I.

The on-board equipment of the simplest semiactive radar homing system, just as in the active system, consists of a target-tracking circuit (the orientation device) and a missile-control loop. The missile-control loop does not differ in any way from the analogous circuit in the active system. The target-tracking loop differs in that it does not contain a transmitter and in that it consists of a re-

ceiving device and a directed antenna that are both mounted in the missile's nose; in addition, the target-tracking circuit includes a control unit and a computer. The antenna beam has a conic sweep, i.e., it rotates about the optical (central) axis of the antenna along the generatrix of the cone, forming a directivity pattern with an equal-signal zone, in order to select and track the target by direction, as is done in the active homing system. The antenna system of the orientation device, as in all homing systems, is mounted on a stabilized platform which makes it possible to use various guidance methods for the missile.

The semiactive guidance system (Fig. 64, version I) exhibits a significant shortcoming in comparison to an active system and we have reference here to the fact that there is, in this version, no possibility of selecting and tracking a target by range, since it is impossible to measure the time between the instant of pulse emission from the transmitter and the instant of reception of this pulse by the missile. This shortcoming may result in a situation in which a missile directed at a particular target will leave its proper heading or arbitrarily change the guidance target upon the appearance of some other target in the field of view of its antenna. Therefore, in addition to a receiver and an antenna (mounted in the nose of the missile) in the case of semiactive guidance systems an additional auxiliary receiver and antenna (Fig. 64, version II) is frequently installed in the tail of the missile, and the antenna is directed backward to receive the pulses from the radar unit. This makes it possible to synchronize the missile-guidance system with the mobile outside irradiation radar unit in order to make possible the measurement, by the missile, of range or rate of change in range. In such a semiactive system a strobe pulse is developed, and this makes it possible to

select and track only the desired target (Fig. 65).

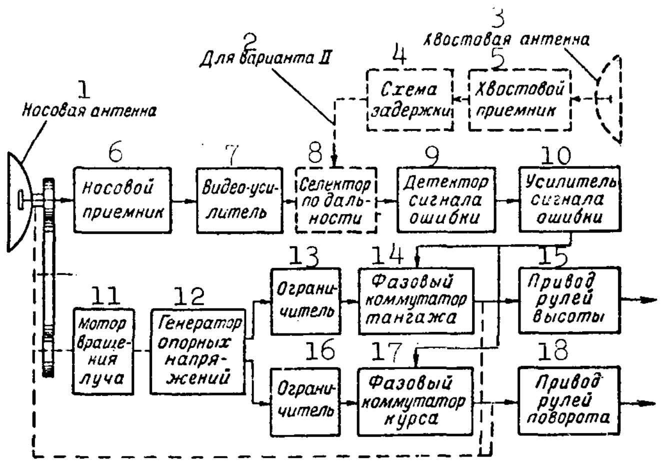

Fig. 65. Simplified block diagram of semiactive radar homing system. 1) Nose antenna; 2) for version II; 3) tail antenna; 4) delay circuit; 5) tail receiver; 6) nose receiver; 7) video amplifier; 8) range selector; 9) error-signal detector; 10) error-signal amplifier; 11) motor for beam rotation; 12) reference-voltage generator; 13) limiter; 14) pitch phase commutator; 15) elevator drive; 16) limiter; 17) heading phase commutator; 18) rudder drive.

The sequence of action in the launching of a missile and the selection of a target in semiactive systems remains basically the same as when active systems are employed. However, a characteristic feature of the semiactive homing system is the fact that after the launching of the missile the illuminating radar unit must remain directed at the target and continuously track the target (and in certain cases provide for the transmission of a synchronizing signal to the missile through the tail antenna of the missile) throughout the entire period of missile flight to the target, and this indicates that so long as the missile is in flight an attack can be carried out only against a single target, although if time and circumstances permit any number of missiles may be launched against this target.

When using semiactive systems it becomes theoretically possible to launch missiles from other directions with respect to the radar-target irradiation direction as well, and this makes it possible, if necessary, to separate the position of the radar unit and the launching installation by great distances. But in these cases, if the radar unit must provide for the transmission of a synchronizing signal to the missile through the tail antenna of the missile in addition to its function of irradiating the target, limitations are imposed on such a semiactive homing system and these are functions of the width of the irradiating radar pattern and the maneuverability of the missile immediately after launch.

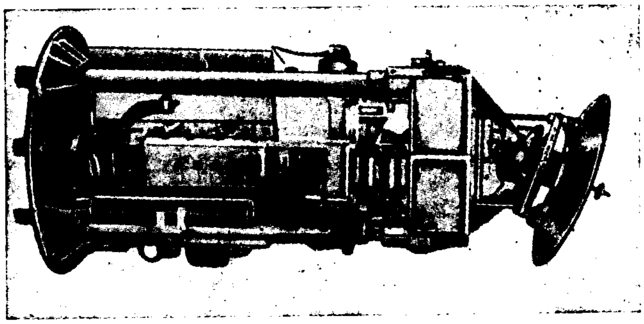

Fig. 66. Outside view of semiactive radar homing head in a guided missile.

Moreover, there is the possibility in semiactive systems continuously to monitor the operation of the radar unit and the operator can always verify that the desired target is the one being tracked. In an active system there is no such possibility after the missile has been launched.

Because the radar transmitter has been removed from the missile, the power of the transmitter can be increased; therefore, as a rule, all semiactive homing systems have a greater guidance range than do active systems.

The maximum effective range of a semiactive homing system can be

expressed by means of the same formula as was cited for the active system, but we must take into consideration that the parameters of the receiving unit remain the same as in the case of an active system, and the parameters of the transmission unit are different from the case of an active system and may be substantially higher, i.e.,

$$Д_{па}=\sqrt[4]{\frac{P_{1изл}\eta_1\eta_2\pi D_1^2 D^2 S_ц}{64\lambda^2 P_{min}}},$$

where D_{pa} is the effective range of the semiactive system; P_{1izl} is the emission power of the radar transmitter; $\eta_1 \approx \eta_2$ are the coefficients by means of which we characterize the level of intersection between the directivity patterns of the transmitting antenna of the radar unit and the receiving antenna of the missile with their optical axis (approximately 0.7-0.8); D_1 is the diameter of the transmitting antenna ; D is the diameter of the receiving antenna (in the missile); S_{ts} is the effective area of the target; λ is the wavelength; P_{min} is the threshold sensitivity of the receiver (in the missile).

In this case it is necessary to bear in mind that the maximum range of a semiactive system is characterized by the product of two ranges: the range D_{per} from the transmitter of the radar unit to the target, and the range D_{pr} from the target to the receiver aboard the missile, and these quantities may vary, and may vary even more with respect to one another during the guidance process. It is characteristic of the given case that the product of these ranges $D_{per}D_{pr}$ remains constant:

$$Д_{па}=\sqrt{Д_{пер}Д_{пр}}=\text{const},$$

and this means that these ranges may, during the guidance process, be redistributed as required, provided that the following condition is satisfied: D_{per} will not exceed the range of the automatic radar

tracking unit.

Hence it follows that if the semiactive system is turned on prior to the launch and the missile is situated close to the radar unit, these ranges will be identical and equal to the maximum effective range of the semiactive system, i.e.,

$$Д_{па} = Д_{пер} = Д_{пр}.$$

Another system can be employed for the initial guidance of the missile, the guidance range may be increased by the following redistribution of ranges:

$$Д_{пр} < Д_{пер} \leqslant Д_{асрп},$$

where D_{asrp} is the maximum range of the automatic radar tracking unit.

Let us compare the maximum effective ranges of the active and semiactive homing systems for the case in which neither system is employed for initial guidance. Assuming $\eta_1 \approx \eta$ we will obtain

$$\frac{Д_{па}}{Д_{ао}} = \sqrt[4]{\frac{P_{1изл} D_1^2}{P_{изл} D^2}}.$$

If we assume, in approximate terms, that the radiated power of the radar unit in the semiactive system is $P_{1izl} \approx 5P_{izl}$ and the diameter of the antenna $D_1 \approx 5D$ (where P_{izl} and D are the parameters of the active homing system), we will obtain

$$Д_{па} \approx 3{,}3 Д_{ао}.$$

Thus approximate calculations of the maximum effective range of the semiactive system may exceed the maximum effective range of the active system by a factor of more than 3.

However, the absolute magnitude of transmitter power, and consequently, the theoretical effective range of the guidance system, are functions of the position of the radar unit (on the ground, on a ship, in an aircraft), i.e., in essence these are functions of the class of

missile for whose guidance a semiactive system is used. For example, there are serious limitations in an aircraft with regard to weight and the dimensions of the equipment used. Therefore, there are no possibilities of significantly increasing the power of the transmitter in an aircraft. On a ship and on the ground it is possible to use radar stations of very great power; therefore, the effective range of semiactive homing systems, such as used for ground and ship-board missiles, is always greater than in the case of aircraft homing systems. According to reports in the foreign press, the semiactive homing system is sufficiently reliable for distances under 30 km.

The semiactive radar homing system may be used for the same classes of missiles as the active system, i.e., for missiles of the following classes: "air-to-air," "air-to-ground," "ground-to-air," and "ground-to-ground." In the latter case the possibility of using such a system is extremely problematical and theoretically possible only for the subclasses "ground-to-ship" and "ship-to-ship." For each of these missile classes the tactical features of their utilization differ from the tactical features that are encountered in the utilization of active homing systems.

For missiles of the class "air-to-air" the semiactive system differs from the active system in that with the utilization of an active system the carrier aircraft can fly in any direction after the launching of the missile or it can attack some other target; in the case of a semiactive system, the carrier aircraft is not free, since the radar unit aboard the aircraft must constantly irradiate the target until the missile encounters the target. In this case, the maneuverability of the carrier aircraft is extremely restricted. The restriction of the maneuverability of the carrier aircraft depends on the width of the beam and the maximum angle of rotation for the antenna of the irradiating

radar unit, and it also depends on the manueverability of the missile and the number of missiles launched or intended for launch against the given target.

For missiles of the class "air-to-ground" it is characteristic, when compared with the class "air-to-air," that the target being attacked is either in a fixed position or is moving slowly; therefore the time factor is not so important in the attack. Consequently, there is no need to launch several missiles simultaneously against a single target, since new attacks may be launched if the missile should fail to strike the target or if the effect produced by the striking of a single missile against the target is inadequate. This pertains in equal measure to active and semiactive systems. The difference here lies in the fact that in the given case the radio unit aboard the aircraft must illuminate the target until the missile strikes it, which forces the carrier aircraft to remain in the vicinity of the target until completion of the missile-guidance process.

In the case in which a semiactive homing system is used, and this applies particularly to missiles of the class "ground-to-air," there is a possibility of using a combined guidance method in which, during the first stage of the approach to the target, another guidance system may be employed; after the missile has been guided to the prescribed point, the semiactive system takes over. This makes it possible to increase even further the effective range of the semiactive system.

In all other ways the advantages and shortcomings of the active homing system apply to the semiactive system.

Manuscript Page No.	[List of Transliterated Symbols]
122	об = ob = ob'yektiv = objective
122	ц = ts = tsel' = target
122	атм = atm = atmosfera = atmosphere
122	опт = opt = optika = optical system
123	пор = por = porogovoy = threshold
140	ас = as = aktivnaya sistema = active system
140	изл = izl = izlucheniye = radiation
150	па = pa = poluaktivnyy = semiactive
150	изл = izl = izlucheniye = emission
150	пер = per = peredatchik = transmitter
150	пр = pr = priyemnik = receiver
150	аспр = aspr = avtomaticheskoye soprovozhdeniye radiolokatora podsveta = automatic tracking unit

Chapter 7

EXTERNAL GUIDANCE SYSTEM

§1. BEAM-RIDER GUIDANCE SYSTEM

The system used to direct a guided missile to a target along a radar beam consists of a radar guidance unit with conic sweep at the control point and of equipment aboard the missile to receive the emission of the radar guidance unit and to work out independently the control signals which will force the missile to fly along the axis of

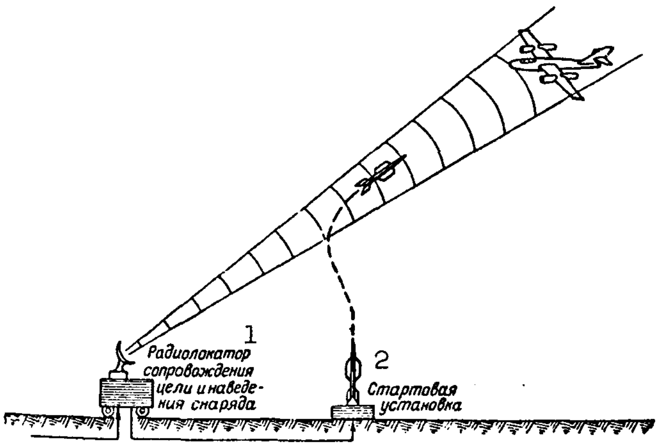

Fig. 67. Single-beam guidance system for missile along radar beam (the three-point guidance method). 1) Radar unit for tracking of target and missile guidance; 2) launching site.

rotation of the radar beam.

As was indicated in Chapter 4, there are two types of beam-rider guidance systems. One of these systems involves the direction of the missile to the target by means of a single radar unit (Fig. 67) which automatically tracks the target, continuously tracking the target

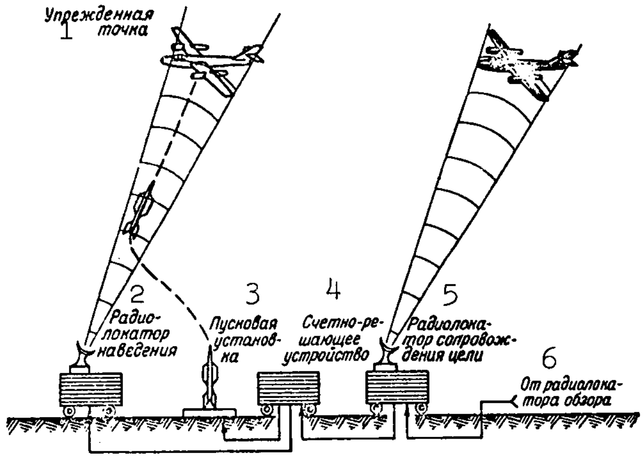

Fig. 68. Two-beam system for guidance of missile along radar beam (method of guidance to predicted point). 1) Predicted point; 2) radar guidance unit; 3) launching site; 4) computer; 5) target track radar; 6) from space radar.

against which the missile is being launched. The missile moves toward the target along the beam of this radar unit.

The other version of the system provides for the utilization of two radar installations (Fig. 68), of which one is a conventional automatic target track radar unit which works out all of the necessary data regarding the target, while the other unit is a simple radar transmitter which emits a rotating beam along which the missile moves. The guidance transmitter whose beam is directed to intercept the target controls the computer on the basis of the target data developed by the target track radar unit.

The second version of the beam-rider guidance system may be executed in another way. Instead of the first radar unit tracking the target, an optical system may be employed, and this system will supply the instantaneous coordinates of the target to the computer.

Simpler versions of these systems (for example, used for missiles of the "air-to-ground" class) provide for the simple coupling of the

optical system tracking the target with the antenna of the radar unit along whose beam the missile is guided to the target. The coupling is carried out so that the axis of the radar beam coincides or almost coincides with the line of sight of the optical aiming device. The systems make it possible to guide missiles along a radar beam against targets which do not offer any radar contrast but can be observed by means of optical sighting devices.

Let us examine the principle of guidance employed in the system with a single radar unit. In this case the radar guidance unit is a radar unit that automatically tracks the target and consists of a transmitter, a receiver, an antenna with a rotating vibrator, and antenna drives which turn the antenna in the direction of target motion. The operating principle of this radar unit is analogous to the one described above. The antenna of this unit shapes a beam that is deflected with respect to its optical axis and which, with the turning of the vibrator, also rotates, thus producing a zone of irradiation in the form of a cone about its axis of rotation (see Fig. 59). The conic zone of irradiation produced by the rotating beam of the antenna is frequently, for the sake of simplicity, simply referred to as the guidance-radar beam. When we say that the missile is being guided along a radar beam, we have in mind the guidance of a missile along the axis of this zone of irradiation.

The missile which carries a receiver whose antenna is directed backward enters the beam after launching and begins to receive radar signals from the radar guidance unit. The operating principle of the guidance equipment installed aboard the missile is similar to the operating principle of the receiver portion of the target track radar, also described above. If the missile flies along the axis of beam rotation in the equal-signal zone, the receiver in the missile receives

signals of identical amplitude during the period of beam rotation. Any deflection of the missile from this axis results in the appearance of amplitude modulation of the received signals at the frequency of beam rotation. The modulation amplitude (modulation factor) of the signal is proportional to the magnitude of missile deflection [deviation] from the axis, and the phase of the signal characterizes the direction of deviation.

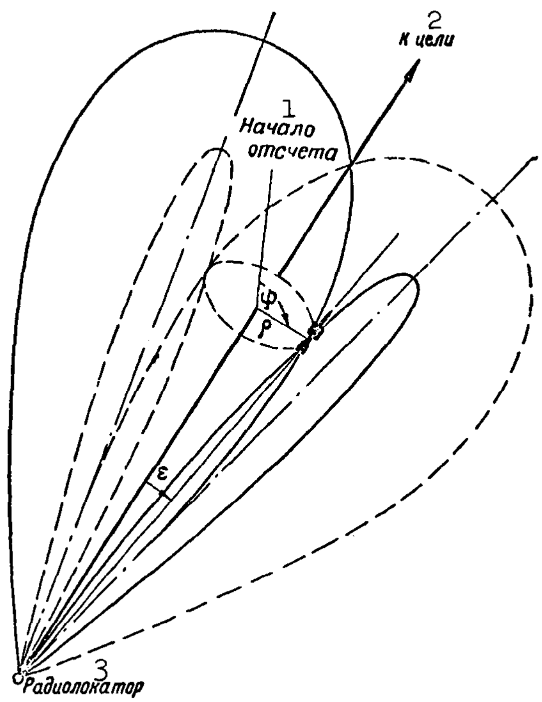

Fig. 69. Coordinates characterizing the position of the missile in the radar beam: ε) The angle between the axis of beam rotation and the direction to the missile; ρ) radius vector from beam axis to missile; φ) angular coordinate of missile in polar system of coordinates; 1) Origin; 2) to target; 3) radar unit.

The received signals are detected and as a result of this detection an error-signal voltage is generated. In order to obtain control voltages it is necessary for the error-signal voltage to be com-

pared with the reference voltages which are formed aboard the missile in accordance with the data from the guidance station. To obtain reference voltages aboard the missile the guidance radar unit must emit special coded signals. A comparison of the phase of the reference voltages with the phase of the error-signal voltage makes it possible to determine the direction of missile shift with respect to the axis of beam rotation and to obtain the corresponding signals for missile control in the heading and pitch channels.

Since the frequency of the variable reference voltage generated aboard the missile must be synchronous with the frequency of beam rotation (the scanning frequency) of the radar guidance unit, a reference-voltage generator for the guidance radar unit is generally employed to form the codes which contain the information that is required for the formation of the reference voltage aboard the missile. The transmission of such information to the missile may be accomplished in a number of ways which make it possible easily to separate the modulation of the reference voltage from the amplitude modulation that represents the error signal (for example, by the frequency modulation of the transmitted signals).

The error signal released in the missile contains intelligence regarding the position of the missile within the beam, in the polar coordinates (ρ, φ). In order to use this intelligence to control the missile with respect to pitch and heading it is necessary to convert the received intelligence into rectangular coordinates. This is accomplished by means of the computer.

The spatially shifted position of the missile with respect to the rotation axis of the guidance radar beam may also be determined by conical coordinates (Fig. 69): by the angle ε between the axis of beam rotation and the direction to the missile, the latter determined

by the depth of the amplitude modulation of the error signal, and by the phase angle φ determined by the phase detector with the aid of the reference voltage. To make possible the control of the missile the conical coordinates must be converted into cylindrical coordinates, for which purpose only a single angular coordinate ε is converted into the coordinate ρ which represents the radius vector from the axis of the beam to the missile. These cylindrical coordinates, which are polar coordinates for each specific instant of time, are converted into the rectangular coordinates (x, y) so that the obtained signals can be used to control the control surfaces of the missile in two mutually perpendicular directions.

In the beam~~-radar~~ guidance system the missile, as a rule, is stabilized for roll and guidance is executed on two channels.

If the missile is deliberately permitted to rotate, the spatial coordinates of the missile (x, y) are converted in the missile to the coordinates (x', y') that are rigidly associated with the missile itself, as a result of which the command signals are also recalculated from one system of coordinates to the other. This recalculation is carried out by means of the computer that is connected to the roll gyroscope.

The control cycle is concluded when the command signals to the autopilot, and from there to the control units, bring the missile to the beam axis and set the control surfaces in neutral position.

In the first version of the beam-rider guidance system the missile is always guided in accordance with the three-point method, i.e., the missile is always in a straight line between the radar guidance unit and the target throughout the guidance process. The flight trajectory of the missile in this instance is such that as the distance between the missile and the target is reduced

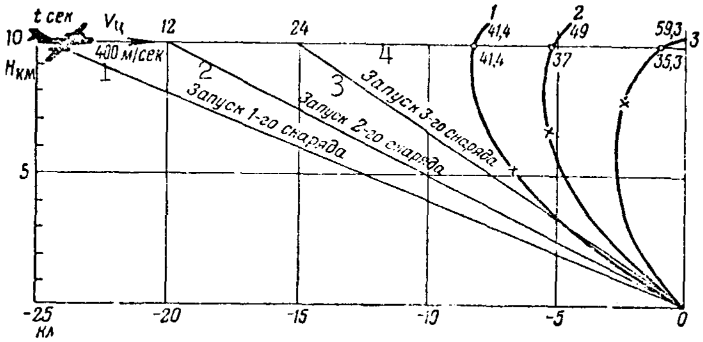

Fig. 70. Approximate trajectories of missiles launched at definite intervals of time from a single launching site and against a single target (the three-point beam-rider guidance method): x) instant of end of engine operation; 1) 400 m/sec; 2) launching of the 1st missile; 3) launching of the 2nd missile; 4) launching of the 3rd missile.

the curvature of the trajectory is increased (Fig. 70). The distortion of the trajectory of missile flight, guided along the beam, is even further increased after the end of engine operation and this can be explained by the drop in missile velocity during the passive phase of the missile flight.

In the case of guidance against a moving target the missile almost always flies at some angle to the beam axis. This angle generally increases as the missile moves farther away from the guidance radar unit, as a result of the increase in the curvature of the trajectory. Moreover, during flight the missile may rotate and assume any position with respect to the transmitting antenna. As a result, the utilization of a single antenna on the missile will have a negative effect on guidance, since the magnitude of the signal received by the missile will fluctuate markedly. In order to eliminate this phenomenon, the receiving device in the missile functions with several antennas (usually four) which are connected to the general guidance circuit.

In the case of missiles whose wings and stabilizers are positioned

in the form of a cross it is convenient to position four antennas at the trailing edges of the stabilizers or in special grooves at the rear end of the missile frame. In these cases small-scale antennas are used. Slot-type antennas installed or made flush with the skin of the frame are very convenient.

This branched antenna system may also be used advantageously because the glowing gases escaping from the nozzle of the rocket absorb to a great extent the emitted signals and attenuate reception. Some single antenna may always be screened by a stream of glowing gases in any of the various positions in which the missile finds itself. By positioning four antennas in mutually perpendicular directions reliable reception is assured for virtually any of the possible positions of the missile in the beam and for any polarization of the signal.

In order to provide for more exact missile guidance to a target great requirements are imposed on the transmitting antennas, their characteristics, and the stability of the transmitter. The antenna must form the beam to a rigorously correct shape, and the transmitter must maintain constant emission power so that during the period of antenna rotation the strength of the emitted signal remains constant in the equal-signal zone.

In the beam-rider guidance system the accuracy of guidance is impaired in approximate proportion to range as the missile moves away from the radar unit. In order to reduce the guidance error at limit range it is necessary to make the beam as narrow as possible. Therefore, this system employs a beam that ranges in width from 3 to 0.5°. The conic angle of the surface described by the axis of the rotating beam is set at less than twice the width of the beam.

However, if a somewhat too narrow beam is used, other problems arise, i.e., difficulty in aligning the missile in the narrow beam

during launching and increasing the possibility of having the missile depart from the beam in the case of rapid shifts in the beam as a result of sharp target maneuvering.

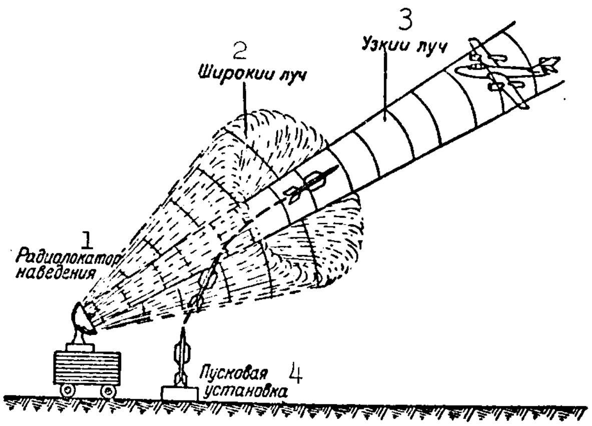

Fig. 71. Beam-rider guidance system (narrow beam) and the system employed to align the missile on the beam (wide beam). 1) Guidance radar unit; 2) wide beam; 3) narrow beam; 4) launching site.

In order for the missile to enter the beam it must be launched from a site that is directed (frequently by means of a special computer installation) so that the motion of the missile during the launch follows a direction close to that of the beam axis, and as close as possible to this axis. The more exactly the direction of missile flight at launching is made to coincide with the direction of the beam axis, the smaller the transient response after missile lock-on and the time at which the on-board guidance system begins to function, thus bringing the missile most rapidly to the beam axis. If the entry angle of the missile into the beam is sufficiently great the missile may pass straight through the beam, there will be no lock-on of the missile by the beam, and the missile will be lost.

To enhance the entry of the missile into the beam, various beam-gathering systems are employed during the launch. The most popular beam-gathering (capture) system is the system which employs a second

transmitter with another antenna system which forms an additional wider beam (Fig. 71). This wide, or in other words, coarse beam is intended for the initial capture of the missile and to gather it into the narrow or more exact beam. A missile, on entering the wide beam, is guided in this beam in accordance with the same principle as applies to the narrow beam, striving to enter the equal-signal zone of the beam. The axes of rotation of both the wide and narrow beams are close to one another or coincide exactly. As the missile enters the equal-signal zone of the wide beam the missile is actually in the effective zone of the narrow beam. During this time the missile automatically executes the switching of the guidance procedure from the wide beam to the narrow beam.

The wide beam is very much wider than the narrow beam. If the narrow beam is 3° wide the wide beam is generally 20° or more wide. Sometimes the width of the beam is of the order of 60°. The antennas of the wide and narrow beams are generally positioned on a single axis of a rotating device and are equipped with a common motor drive for purposes of rotation. The speed of antenna rotation may be 100 rpm and higher.

The wide-and-narrow beam transmitters emit signals that differ in frequency, but these frequencies are close to one another. The signals are received aboard the missile by a single antenna (if there are four antennas, then these signals are received by each of the four) and are separated into the wide- and narrow-beam channels by means of frequency filters. Then the signals are strengthened by means of the amplifiers that are provided individually for each channel.

The switching of control from the wide beam to the narrow beam is accomplished by means of a relay which is controlled by the modulated voltage of the wide beam and the switching is executed at the instant

at which the modulation factor of the wide-beam signals drops below a certain set magnitude. The magnitude of the voltages across the wide- and narrow-beam channels, proportional to the modulation voltages, are evened out so that in switching from one beam to the other there should be no discontinuity in voltage capable of disrupting smooth and continuous guidance.

If a missile being guided to a target along a radar beam is launched from an aircraft, the installation of a second transmitter for a wider beam is not feasible. Therefore, in such cases other beam-gathering systems are employed. However, the launching of a missile must always be carried out in the direction in which the carrier aircraft is flying.

In order to prevent the missile from escaping the beam as it is being guided against a fast-moving or highly maneuverable target, the width of the beam must be increased somewhat and this results in a situation in which the equipment aboard the missile must function at smaller field-voltage differences both in the center and at the edges of the beam; as a result, more sensitive receiving devices must be installed aboard the missile.

In the case of the second beam-rider guidance system, in which case the target is tracked by means of a single radar unit, and the guidance of the missile is carried out by another radar unit (a single transmitter), no expansion of the radar beam is required. In this case, with the narrow guidance radar beam a special computer device is employed and this unit, on the basis of the data received from the automatic target track radar unit, not only calculates the point of contact between the missile and the target but also works out the corresponding program of guidance radar-beam movement which will prevent any excessively rapid shifting of this narrow beam in

space. As a rule, this system guides the missile to the target in accordance with the lead-point method. However, in addition this program may include the following: the rapid attainment by the missile of the most economical cruising altitude, and subsequently as the missile approaches the target, it is capable of flying at certain steep-dive or pitching angles.

Regardless of the beam-rider guidance system used, the accuracy of guiding a missile to a target depends, in great measure, on the accuracy of the tracking of the target with respect to the angular coordinates, and this in turn is a function not only of the beam width and the stability of the transmitter, but of the fluctuation (extinction) of the reflected signal. In tracking a moving object, definite reflected-signal fluctuations appear at the output of the receiver installation of the target track radar, and these fluctuations are functions of the shape and dimensions of the object and the nature of its motion. These fluctuations, to a greater extent than the internal noise of the radar receiver, disrupt the tracking process and restrict the accuracy of tracking an object. To reduce the degree of their influence, it is desirable to compare the obtained signal levels for various beam positions as quickly as possible, i.e., it is desirable to rotate the beam as rapidly as possible. However, the speed of beam rotation is limited by the mechanical possibilities as well as by the number of pulses that can be ascribed to the target, i.e., the number necessary for reliable reception and sufficiently accurate determination of the amplitude and phase of the envelope after the detection of the signals.

The accuracy of target tracking is restricted primarily by the fluctuation component of the reflected signal on a frequency close to that of beam rotation and by the harmonic components of this frequency.

The magnitude of these components is proportional to the passband of the directional tracking system (the angular-coordinate target-tracking circuit), which, consequently, should desirably be reduced to the minimum permitted by the nature of the object's motion. For example, in tracking a slow-moving ground or naval target the passband of the system may be made extremely small; in tracking aerial targets the passband must be greater, i.e., in proportion to their greater speed.

If the passband of the directional tracking system were changed in inverse proportion to the range, it would be possible to increase the accuracy of determining the data at great distances from the guidance point where the angular velocities and accelerations of beam shifting are small, but where a small error in angle would result in great linear deviations. An increase in the band at small distances, however, will not result in any reduction in linear accuracy in tracking high-speed aircraft.

The guidance system which employs a rotating radar beam makes it possible to detect a shift in the target (or a shift in the missile) by less than 0.1 of the width of the beam.

The beam-rider guidance system gained widespread practical acceptance because of its comparative simplicity and adequate high guidance reliability. The simplest systems of this type (for example, aircraft) have rather uncomplicated equipment at the control point and rather simple on-board equipment (a transmitter on-board the missile is not required).

The beam-rider guidance system is employed for missiles of the following classes: "ground-to-air," "air-to-air," and "air-to-ground"; however, this system is used primarily for the guidance of anti-aircraft missiles.

Beam-rider guidance systems may also be employed to control

ballistic missiles of the "ground-to-ground" class during the initial phase of the flight trajectory (Fig. 72).

The effective range of the system is not too great and is completely determined by the effective range of the target track radar and the missile radar guidance units. The effective range of the system is only a weak function of meteorological conditions. An advantage of this system is the possibility of simultaneously guiding several missiles along a single beam against a target (or group of targets). But since the radar beam tracking the target must be directed at the target throughout the entire time of missile flight, until the attack against a single target is completed it cannot be transferred for use in the guidance of missiles to other targets. This circumstance, moreover, in the case of guidance of the "air-to-air" missile class restricts the maneuverability of the carrier aircraft which must fly so as to execute the least possible lateral movement on the part of the missile in order to avoid losing it.

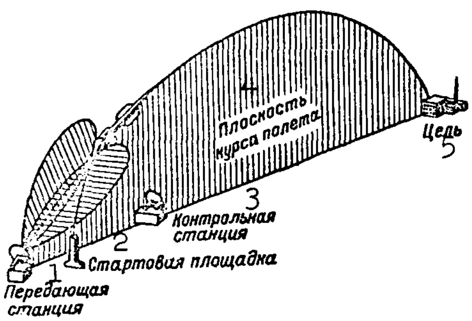

Fig. 72. The beam-rider system for the guidance of ballistic missiles during the initial portion of the flight. 1) Transmitting station; 2) launching site; 3) control station; 4) plane of flight heading; 5) target.

A shortcoming of the beam-rider radar guidance system is the fact that as the missile moves farther away from the radar unit, i.e.,

as the missile approaches the target, the accuracy of guidance is diminished, while at this particular instant an increase in accuracy is required. To eliminate this shortcoming in the guidance of missiles against distant targets, this system is used in combination with a self-guidance (homing) system that is generally semi-active; this system is actuated during the last stage of the missile flight.

Another shortcoming of the system is its sensitivity to the effect of radar interference produced by the enemy. Such interference may be produced by a jammer carried by the targets against which the missile is being launched, as well as by metal-coated strips scattered in the air and capable of decoying the guidance beam from the target.

§2. COMMAND GUIDANCE SYSTEMS

In command guidance systems, which can be made in a great many versions, the missile is guided against the target by means of special commands that are transmitted in some manner from a command station to the missile for purposes of changing the missile's trajectory in accordance with the adopted guidance method.

To provide for guidance this system must observe the motion of both the missile and the target from a command station and determine their mutual position; in addition, the system must provide for the calculation of errors in missile trajectory, work out control commands, and transmit these to the missile where the on-board control system must evaluate these and guide the missile along the required trajectory.

The evaluation of the magnitude of missile deflection from a given heading (guidance errors) and the determination of the nature (selection) of the required signal transmitted to the missile for the elimination of the error is sometimes accomplished visually (manually) in these systems by the operator, but most frequently this is done automatically by means of computer installations. Depending on the

manner in which the foregoing is accomplished, command systems are divided into nonautomated systems (with manual control) and automated systems.

Depending on the nature of the target, the class of the missile, and the guidance method, the monitoring of the mutual position of the missile with respect to the target may be accomplished in various ways (see Fig. 36). The monitoring line may be visual, or it may involve optical, radar, or television equipment. The monitoring of the mutual position of the missile and the target may be carried out either by means of a single common monitoring facility employing a common "indicator" — in the case of guidance, for example, by the method of three points; or separately, by a single facility to monitor the missile and another facility to monitor the target, this method employed in the case of the lead-point guidance method, etc. In certain cases in order to guide the missile to a target it is sufficient to keep only the mutual position of missile and target under control without determining their exact coordinates; in other cases the exact measurement of position and the elements of missile and target motion are required, i.e., in the latter case the intelligence must contain the angular coordinates, the range, and their time derivatives.

The selection of target-observation facilities is determined by the type and nature of target motion. For example, for ground targets whose movement is slow, simpler observation facilities may be employed. If the target is fixed there is no need in maintaining its position under constant observation. The motion of high-speed aerial targets calls for the constant observation and continuous tracking of these targets. The best facilities for automatic missile and target tracking are radar stations.

If the monitoring system shows that the missile has deflected

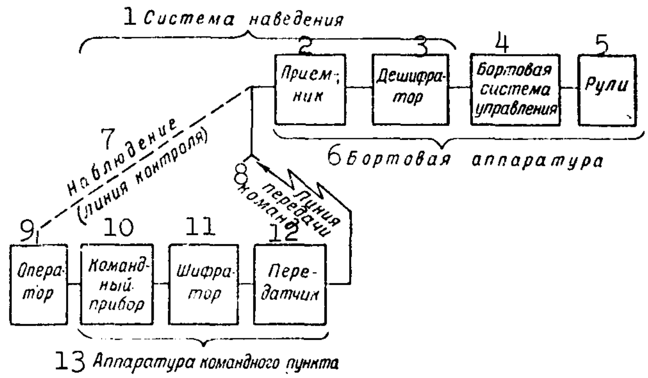

Fig. 73. Block diagram of command system with manual control. 1) Guidance system; 2) receiver; 3) decoder; 4) on-board control system; 5) control surfaces; 6) on-board equipment; 7) observation (monitoring line); 8) command-transmission line; 9) operator; 10) command link; 11) coding unit; 12) transmitter; 13) command station equipment.

from the required trajectory, corresponding command signals are transmitted to the missile over the control link (the command-transmission link). The control link may either be one involving wires, radio lines, or radar equipment; the command guidance systems, depending on the type of control links employed, are classified correspondingly into the following types: systems with wire control, radio control, or radar control.

In order to distinguish one command from another transmitted to the missile, the commands are coded. The coding of the commands, moreover, is made necessary by the need to eliminate (or reduce) the influence of natural interference and the possibility of deliberate enemy interference, which might disrupt the normal control of the missile. The necessity to code control commands calls for the incorporation of a coding unit into the system at the command station and for the inclusion of a decoder aboard the missile.

The coding of signals is employed in all command systems, regard-

less of whether they are nonautomated or automated. In the case of the nonautomated systems coding is accomplished manually by the operator through the coding unit of the command device, whereas in the automated systems this operation is carried out by a computer.

For the formation of commands in command installations mechanical or electrical signal-coding systems are generally employed. The former are used, as a rule, in the manual command systems, while the latter are generally employed in the automated systems.

There exist various methods of coding signals: coding with respect to quantitative and qualitative indicators, coding [sic], and combined coding. In the case of coding with respect to quantitative and qualitative indicators the transmitted signal is distinguished in terms of polarity, amplitude, quantity and duration of pulses, repetition rate, and other characteristics. In the case of coding [sic] the formed signal is composed of several qualitatively different pulses transmitted according to a definite sequence. Coding [sic] provides the system with stability against natural and artificial interference. The most complex method is the one which involves combined coding which employs a complex system of signals sometimes transmitted simultaneously over several channels. In this case the command will be executed upon receipt of the entire aggregate of signals over all channels. Such coding always makes difficult the interception and analysis of the transmitted signals and provides for the most reliable protection against enemy interference.

The commands formed in the command or computer device are transmitted to the modulator which controls the command radio- or radar-transmitter which transmits commands to the missile through its antenna in the form of modulated radio signals.

To distinguish the coded commands a decoder is mounted in the

missile and this unit exhibits selective properties. The received and decoded signals are directed to the corresponding channels and in accordance with their designation control the functioning of definite servo loops.

Thus the equipment of a typical command guidance system consists of the comparatively simple on-board missile equipment consisting of a receiver with an antenna, command signals, and a decoder, and a simple or more cumbersome and complex (depending on the complexity of the system) piece of equipment at the command station which includes facilities for observations of both missile and target (in certain cases, observation of one of the targets), a manual command device or a computer device with a coding system, and a command transmitter. The block diagram of a nonautomated command system is shown in Fig. 73, and that of an automated system is shown in Fig. 74.

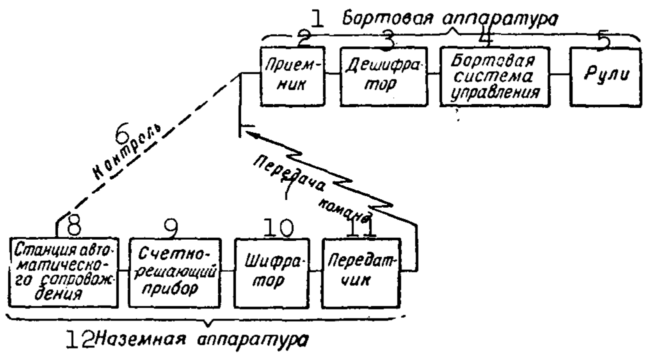

Fig. 74. Block diagram of automated command system. 1) On-board equipment; 2) receiver; 3) decoder; 4) on-board control system; 5) control surfaces; 6) monitoring; 7) command transmission; 8) automatic tracking station; 9) computer; 10) coding unit; 11) transmitter; 12) ground equipment.

The designation of the command guidance system is determined either according to the type of control link or according to the type of monitoring link, i.e., by the element of the system which is

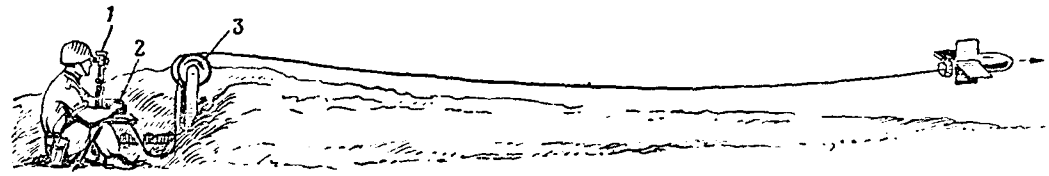

Fig. 75. Operating principle of wire command control system: 1) Optical device; 2) command device; 3) wire form.

characteristic for the particular version of the system. Primarily, we distinguish four types of command systems: a wire guidance system, a radar guidance system, an optical guidance system, and a television guidance system. Certain of these systems, depending on the differing tactical and similar conditions of utilization, appear in a number of versions.

The wire guidance system (Fig. 75) is the simplest of the command systems. It is included among the nonautomated systems. Data regarding the position of the target and the missile are, in this case, received visually, and the missile is controlled by means of pulsed electrical signals transmitted by an operator through a command instrument over two fine insulated wires which unwind (during the flight of the missile) from freely rotating wire forms mounted on the missile itself (generally on the wings of the missile) and at the control point (on the ground or in a carrier aircraft). The advantage of such a system is the simplicity and immunity to enemy interference. However, in the case of great missile flight velocities such a control link would not be reliable in view of the possibility of the separation of the wires. Moreover, the range of the wire guidance system is extremely limited — at best, only several kilometers. Such a system is used in the French antitank "Nord 5200" missiles. These missiles leave a glowing track during flight, making it possible to track their flight exactly by means of an optical sighting device. A

missile of this type, launched approximately in the direction of the target, after entering the field of view of the aiming device is lined up (by the flashes from the tail assembly) with the cross-hairs of the aiming device and directed at the target. The effective range of the system is less than 2 km. The inherent shortcomings of the wire system restrict its utilization markedly.

The optical command system (Fig. 76) is also classified among the nonautomated systems. In this system missile and target tracking and determination of their mutual position is carried out by an operator through optical aiming devices. The transmission of commands to correct the trajectory of the missile is also carried out by an operator over a radio link. Errors that are characteristic of manual control can also occur in such a system and, consequently, the guidance accuracy depends in great measure on the ability and experience of the operator. A simple optical system may be used to guide missiles of the "air-to-air" and "air-to-ground" classes (Fig. 77). In this case, an optical sighting device is mounted on an aircraft, as well as a command device to work out the required command signals, and finally there is a radio transmitter. The on-board equipment of the missile is typical of the majority of command systems. The missile is generally guided in accordance with the three-point method in which it is maintained constantly on the line between the command point and the target. The optical systems in which cumbersome optical theodolites are used to track both the missile and the target are used for the guidance of missiles of the "ground-to-air" class (Fig. 78). However, optical systems have not gained widespread acceptance because of a series of significant shortcomings: low range of visibility, dependence on weather conditions and time of day, as well as because of the complexity of the construction of the theodolite stations, etc.

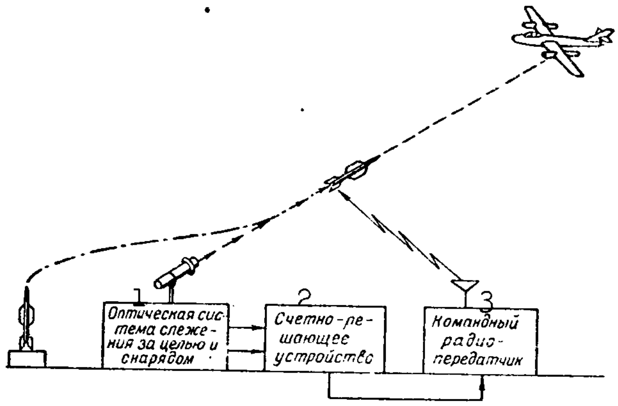

Fig. 76. Diagram of optical command system. 1) Optical system for the tracking of the target and the missile; 2) computer; 3) radio command transmitter.

Radar command systems are improvements over the systems considered above. Depending on the number of radar units in the radar command guidance system, systems are divided into single-beam (with a single radar unit) and dual-beam (with two radar units).

Two types of single-beam radar command guidance systems are known, and of these one is used for the guidance of a missile against a moving target, while the second is employed for fixed targets.

In the first version (Fig. 79) the single-beam radar command system employs one and the same radar unit simultaneously to track the motion of the target and the missile. In this case, the missile moves along a trajectory which is constantly within the line between the command station and the target, i.e., the guidance is carried out in accordance with the three-point method. The launching of the missile and its gathering by the radar beam are carried out almost in the same manner as in the beam-rider guidance system. The determination of missile position with respect to the target or the central axis of the radar beam is carried out on the screen of the target and missile track radar unit.

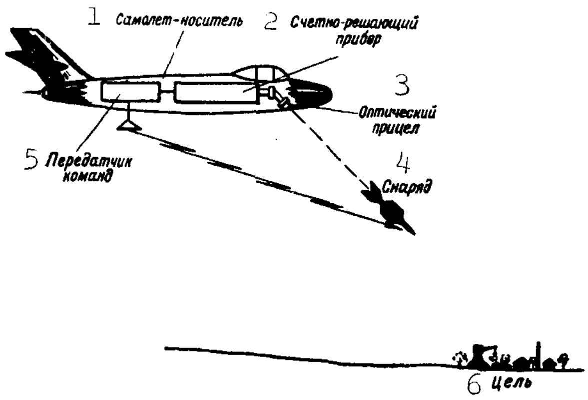

Fig. 77. Utilization of optical command system for guidance of guided missiles of the "air-to-ground" class. 1) Carrier aircraft; 2) computer; 3) optical aiming device; 4) missile; 5) command transmitter; 6) target.

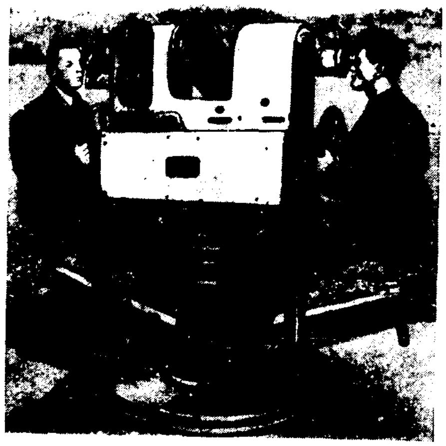

Fig. 78. Over-all view of theodolite for tracking the flight of a guided missile: In the center) telescopic lens; to the left and to the right) tracking telescopes.

To facilitate the simultaneous tracking of both the missile and the target by a single radar unit, a transponder is installed in the missile.

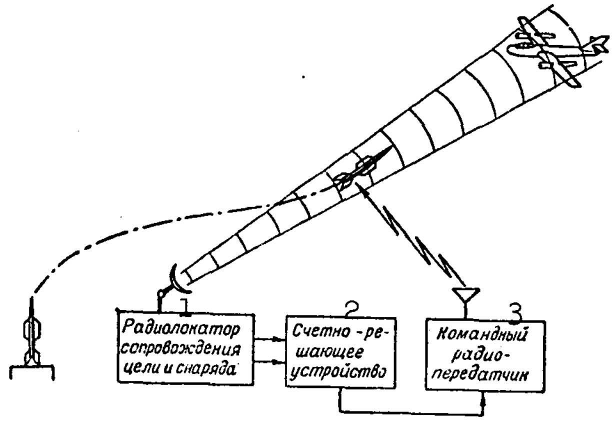

Fig. 79. Diagram of single-beam radar command system: radar unit simultaneously tracks target and missile (radio control). 1) Target and missile track radar; 2) computer; 3) radio command transmitter.

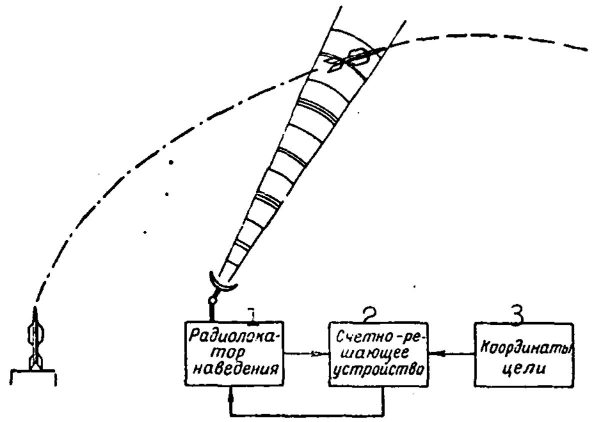

Fig. 80. Diagram of single-beam radar command system: the radar unit tracks the missile, the target is fixed. (radar-channel control). 1) Radar guidance unit; 2) computer; 3) target coordinates.

To provide for the simultaneous tracking of two targets, the tracking radar must be equipped with two individual receivers for separate receipt of signals from both target and missile. The data from the missile and target track radar units (from two receivers) are fed into a computer which determines the errors in missile tra-

jectory and works out the appropriate command signals which are transmitted to the missile by means of the command transmitter over a radio link. In this system more on-board equipment is required in the missile – an auxiliary radar receive-transmit unit (a transponder). This system may be employed in missiles of the "ground-to-air" and "air-to-air" classes.

The second version (Fig. 80) of a single-beam radar command system is used for the guidance of missiles of the "ground-to-ground" class in those cases in which the target is fixed and its position is known exactly. Since the coordinates of the target and the launching site of the missile are known, the flight trajectory of the missile may be calculated in advance and be preset. The guidance radar unit tracks the missile from the instant of launch and continues this procedure generally to the instant at which the engines cease to function, continuously reporting data regarding the position of the missile to a computer which compares the trajectory of the missile with its preset and calculated trajectory, determining the magnitude of any deviation and working out the control commands which are to be transmitted to the missile over the radio link or over the radar beam. This system may be used to guide ballistic missiles over the initial sector of a trajectory. In these cases, the computer controls the instant of engine burnout as well, and the determination of this instant in these cases is extremely important to provide for the exact contact of missile and target. This version of the command system has been dubbed in certain foreign sources as <u>the guidance system with preset trajectory</u>.

The two-beam radar command system is the most perfect and the most complex form of the command system. This form of the system employs two radar units (Fig. 81) that perform their tracking opera-

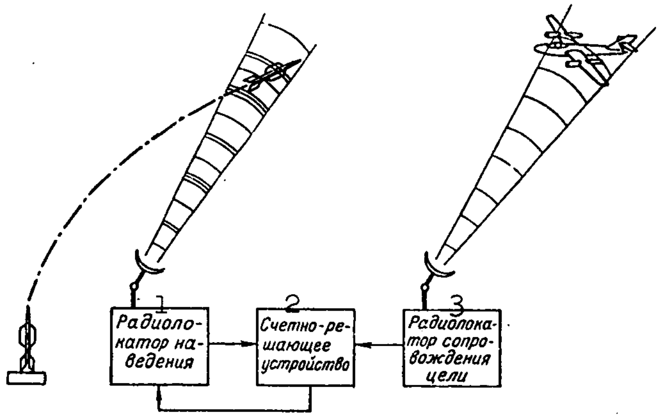

Fig. 81. Diagram of two-beam radar command system (the "Nike" system). 1) Guidance radar unit; 2) computer; 3) target track radar.

tions automatically; one of the radar units tracks the target, and the other tracks the missile. The output signals of the radar units, containing intelligence regarding the target and the missile (angular coordinates and range) are supplied to the computer which, on the basis of these data, automatically calculates the point of missile and target contact, continuously working out the required missile flight trajectory to the target as well as the control commands which provide for the motion of the missile over the given trajectory. The control commands may be transmitted either over the radar channel by means of modulating the signals of the radar unit which tracks the missile, or over a special radio link. This version of the system is employed for the guidance of missiles of the "ground-to-air" class. A typical example of such a system is the one which is employed for the guidance of the American anti-aircraft "Nike" missiles. Various methods may be employed to guide missiles with this system. The given guidance method is carried out by the computer of the system.

The computers used for the command systems may be highly perfected.

These computers, in addition to calculating the point of impact and the missile flight trajectory in accordance with the selected guidance method, may have auxiliary functions and solve a number of other problems. The computer may determine the launching angle prior to launch, calculate the parallax (the correction factor for the distance between the position of the launching device and the radar firing control unit), calculate the trajectory which provides for the greatest firing range, the minimum flight time to a given point, etc. The computer may also calculate the change in the aerodynamic properties of the missile as a result of changes in flight altitude and speed.

The control (or command) links can, in addition to the signals for the control of the control surfaces, also carry such other commands as the regulation of receiver amplification, preparation of the warhead, detonation of the warhead at the target, self-destruction of the missile if it fails to fly its intended course, and other information. The quantity and quality of the transmitted intelligence, the range, reliability, and security of transmission depends on the type of command system employed. Proceeding from this, we determine the type of command link (radar control or radio control), the carrier frequency (if a radio link is selected), the number of channels, the width of the channel, the output power of the transmitter, the sensitivity of the receiver, and the type and dimensions of the antennas.

The effective range of the system is determined by the tactical requirements and depends on the mutual position of the transmitter and receiver during the guidance procedure, and it also depends on the carrier frequency, the power of the transmitter, the sensitivity of the receiver, the dimensions and directivity of the antenna, the conditions of radio-wave propagation in the given region, and on other factors.

The reliability of the system depends on the power of the incoming signal, the conditional propagation of radio waves, and the stability of the system with respect to interference.

Of no mean significance from the standpoint of reliability is the selection of the carrier frequency (wavelength). In the control radio links the centimeter, decimeter, and ultrashort meter wavelengths are most frequently employed. As is well known, with a reduction in the wavelength the antenna dimensions are reduced and the directivity of the antennas is increased. With an increase in transmission directivity the reliability of communications may be reduced. In addition to having to take into consideration these factors, for purposes of increasing system reliability we sometimes recommend, should this become necessary, that the sensitivity of the receiver be made somewhat coarser.

Any command guidance system transmitting command signals to a missile must exhibit maximum screening of transmission, since an enemy will attempt to detect and analyze the control signals in order to interfere through the introduction of false signals or suppression of reception. Detection of transmission may be made difficult by directivity and brevity of radio transmission, and by minimum signal power adequate to maintain communications. Decoding and analysis of transmitted signals is made difficult by the coding [sic] of the signals.

Command systems may be employed for the guidance of all classes of missiles, as well as many subclasses of missiles.

Command systems with visual, optical, and television monitoring systems are included among the manual or nonautomated systems. A serious shortcoming of these systems is the unavoidable delay in the motion of the missile with respect to the motion of the target, en-

abling the target to carry out escape maneuvers during pursuit, thus resulting in an increase in the guidance error. Another shortcoming of these systems is their dependence on the conditions of visibility and weather.

A more flexible and exact command system is the two-beam radar system which is classified as an automated system. The advantage of the radar systems lies in their limited dependence on the conditions of weather and their complete independence of conditions of visibility.

A shortcoming of all command systems is the absence of secrecy and the fact that these systems are subject (with the exception of the wire control systems) to the effect of radio and radar interference generated by an enemy.

Despite the above-mentioned shortcomings, certain types of command systems have gained widespread acceptance.

The television command system, in view of its specific features, is examined separately.

§3. THE TELEVISION GUIDANCE SYSTEM

The television guidance system, or in other words a guidance system with a television head, is a version of the command guidance system in which the control link is still represented by the radio link (radio control), and in which the motion of the missile with respect to the target is monitored by means of a television installation.

Such a system is employed for the guidance of various classes of guided missiles, i.e., primarily in the case of guiding bombs and torpedoes against ground and naval targets whose positions change or have not been determined exactly.

It is absolutely necessary to include a device making possible the transmission of an image of the target and the surrounding area to the command station as part of the television guidance system, and

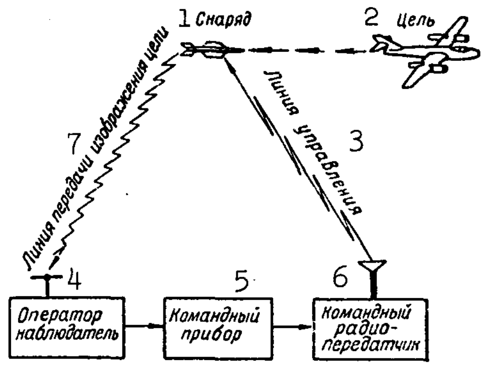

Fig. 82. Diagram of the television command guidance system. 1) Missile; 2) target; 3) control link; 4) observer operator; 5) command device; 6) radio command transmitter; 7) target-image transmission link.

there must also be incorporated a device which reproduces the transmitted image on a television screen. Moreover, there must be a system for the transmission and reception of commands. Thus, the television-guidance system equipment includes the following: aboard the missile, a transmitting television camera, a television transmitter (with antenna), a command receiver (with antenna); at the command station, a television receiver (with antenna), a command device, and a command transmitter (Figs. 82 and 83).

The principle of guiding a guided missile or bomb by means of this system involves the following. The missile or bomb directed at a target projects the image of the target and its surrounding area through an optical system within the television camera onto a transmission tube. This image is transmitted to the command station where the operator may observe, on the screen of a television receiver, whether or not the missile or bomb is accurately approaching the target. For an exact strike against any target, the latter must generally be fixed constantly in the center of the screen. If the missile is

deflected from its proper heading the operator transmits the appropriate command by radio and corrects the trajectory of the missile.

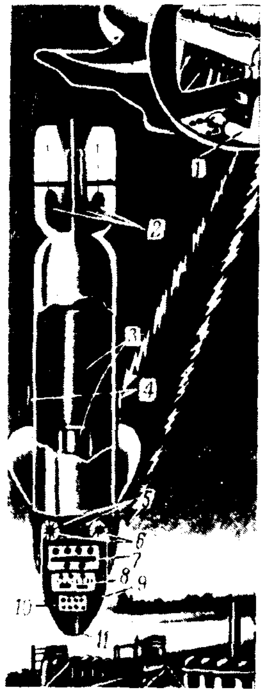

Fig. 83. Guided bomb with television guidance head and its basic elements: 1) Operator aboard carrier aircraft; 2) magnetic tail-surface regulators; 3) explosive; 4) receiver antenna; 5) electric power generators; 6) air turbines; 7) reception device; 8) television transmitter; 9) antenna of television transmitter; 10) television camera; 11) objective (lens).

The efficiency of the television guidance system depends on such basic system indicators as the range at which the television transmission tube begins to distinguish or "see" the target and the range of television transmission. The range of "visibility" of the transmission tube is determined by the sensitivity of the tube and the resolving power of the system. However, the range of television transmission is a function of the power of the television transmitter aboard the missile, the sensitivity of the television receiver at the command station, and the range and conditions of propagation for the ultrashort radio waves employed in television engineering. Thus the effective range of the television guidance system is determined not by the control link (the radio link) whose effective range may be quite great, but rather by the television monitoring link whose range is a function of the range of television transmission.

The quality of the transmitting television equipment is of great significance for missile control. The dimensions and weight of the missile sometimes make it impossible to employ all of the latest achievements of television engineering; however, in order to attain high sensitivity and good

resolving power the best contemporary transmission tubes are employed.

As is well known, the transmission of a television image is possible as a result of the decomposition of the visual image into a multiplicity of minor component parts referred to as picture elements. The greater the number of elements into which an image can be decomposed, the greater the clarity with which the image can be transmitted. The clarity of a television image is characterized by the number of lines into which this image can be decomposed.

The transmission of an image is carried out in the following manner. The subject that must be transmitted is projected through the objective of the television camera onto the photocathode of the transmitting television tube (iconoscope). The light image is converted into electrical pulses at the photocathode and the magnitude of these pulses changes constantly as a function of the luminescence of the photocathode. These pulses are then transmitted to the television transmitter and modulate the emitted power of the television transmitter in accordance with the image that has been fed to the transmitting television tube.

The decomposition and reproduction of an image is possible as a result of the scanning (shifting) of an electron beam over the lines and frames in the transmitting and receiving television tubes, and this scanning procedure must take place with strict synchronization. The electron-beam scanning in which the lines are decomposed successively, one after the other, is referred to as progressive scanning. Frequently another method of beam scanning, referred to as interlaced scanning, is employed. In this case each frame is separated into two half frames, and only the odd lines are transmitted in one of the half frames, while only the even lines are transmitted in the other half frame. This scanning method has the advantage of making possible a

reduction by a factor of two in the frequency band occupied by the television signal during the transmission. This is of significant importance for the multichannel television systems used in missile control, as well as from the standpoint of increasing the sensitivity of the reception devices.

The first American models of the "Blok" television guidance system for glide bombs operated with a standard 350 lines of progressive scanning and 40 frames per second. Here the video-frequency passband was 4.5 Mc. The improved "Blok-III" exhibited higher indicators. Good clarity is provided by the standard adopted for standard television broadcasting, with 625 lines for 50 frames per second and interlaced scanning (25 complete frames). In this case a frequency band of about 5 Mc is required.

Such a wide frequency range calls for the utilization of a section of shorter waves in the ultrashort-wave range. The first pieces of television guidance equipment operated within a range of 100 Mc (on a 3 m wave). Here the antenna dimensions were somewhat too great for guided bombs. In the development of later equipment models the range was switched to 300 Mc (1 m). Here it must be taken into consideration that the shift to shorter waves, in addition to reducing the dimensions and the possibilities of utilizing higher standards, results in a reduction in the effective range of the system, as a result of the greater restrictions on the propagation range of the shorter waves.

Another extremely important characteristic which affects the utilization efficiency of the television guidance system is the sensitivity of the transmission tube. The first television cameras for guided bombs, employing small-dimension iconoscopes, were able to function only with good target illumination, and this substantially restricted the possibilities of using television guidance systems. Only

with the development of a new television transmission tube — the superorthicon — whose sensitivity was increased by a factor of one hundred in comparison with the conventional iconoscopes, made it possible to utilize a television guidance system under conditions of poor visibility, on dark days, or at dusk.

The superorthicon can function normally if its photocathode is illuminated with one-tenth of a lux, and this corresponds to the illumination of the earth's surface on a moonlit night. However, the system is incapable of functioning at night, since this illumination cannot reach the photocathode as a result of atmospheric absorption and the absorption that takes place within the optical system of the transmission camera. The development of the superorthicon substantially expanded the military uses of television guidance systems.

The minimum target dimension which can be resolved by means of a television transmission camera and, consequently, be detected on the screen of a television receiver, is a function of the sensitivity of the transmission tube, the clarity (number of decomposition lines) of the system, and the viewing angle of the camera's objective, the latter being a function of the focal distance. The larger the number of lines in the frame and the smaller the viewing angle of the objective, the tinier the dimensions of the object can be.

The range or altitude at which the television camera is able to provide a clear image of the locality depends on both illumination and the weather. Under favorable meteorological conditions, contemporary television systems make it possible to distinguish targets that are 50 × 50 m in size, at distances ranging between 15 and 20 km. It is possible to detect individual buildings, vessels on rivers, etc., from an altitude of 3000 m. From an altitude of 1500 m it is possible to determine the number and types of aircraft stationed at an airfield.

To improve the contrast of the transmitted image various light filters are employed in these television systems. The transmission cameras may sometimes be equipped with several automatically interchangeable objectives which make it possible to transmit close-ups and long-range shots. In several equipment models special automatic shutters are employed to prevent a reduction in tube sensitivity, should a ray of sunlight impinge directly on the objective.

The weight and the dimensions of the equipment are of great importance from the standpoint of utilizing television systems in missiles and guided bombs. The transition to shorter waves, although resulting in a slight reduction in dimensions, does bring with it a reduction in the range of television transmission. A significant reduction in weight and dimensions of equipment became possible after the development of a miniature superorthicon with a diameter of 5 cm and a length of 22 cm. The utilization of this transmission tube made it possible to develop a small-scale television camera (cylindrical in shape) [Fig. 84] that could be carried conveniently in the nose of the missile. The utilization of miniature tubes and component parts, printed circuits, and transistorized instruments makes it possible to reduce the weight and dimensions of the television equipment even further and thus bring about a reduction in the power required by this equipment, and this is also extremely important.

To improve the reliability and interference resistance of the television guidance system, a number of improvements were incorporated into the apparatus: to eliminate the disturbing effect of signals from radar stations and other sources of interference stable synchronization circuits were developed and an automatic system for the regulation of signal amplification was employed to eliminate the phenomenon of fading. Test results have demonstrated that high-quality transmission

of a television image is possible under conditions of screening the on-board transmission equipment from the effects of acoustic and electrical noise, by maintaining high stability for the synchronizer, and by preserving a large ratio at the point of reception between the intensity of the direct-signal field and the intensity of the field of the signal that is reflected from the surface of the earth.

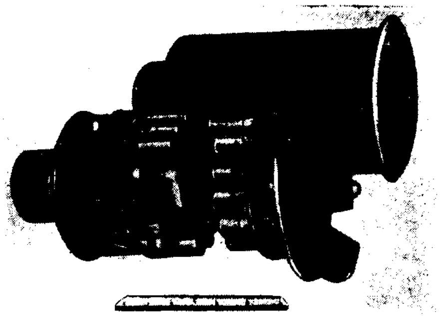

Fig. 84. Over-all view of the construction of the television camera that is installed in the nose of a guided missile.

In certain cases, several channels are employed for the transmission of an image (for example, in the "Blok" system four channels in the frequency range between 78 and 114 Mc are used) to improve the resistance of the system to interference. This utilization of numerous channels, in addition to improving the resistance of the system to interference, makes it possible to guide several missiles (bombs). To improve the resistance of the command-transmission link to interference the control signals are transmitted simultaneously over several frequency channels and this transmission is picked up by a number of miniature receivers aboard the missile. In this case, provision is made for the missile to react to the control signal only in the case of the simultaneous opening of all frequency channels. This makes it difficult for an enemy to interfere with the functioning of the guidance system.

For purposes of greater image contrast during operations under

daytime conditions electron-beam tubes with green screen illumination are generally employed in television receivers installed aboard the aircraft from which the missiles or bombs with television guidance heads are controlled. The interfering effect of dispersed light may also be reduced by means of special green light filters.

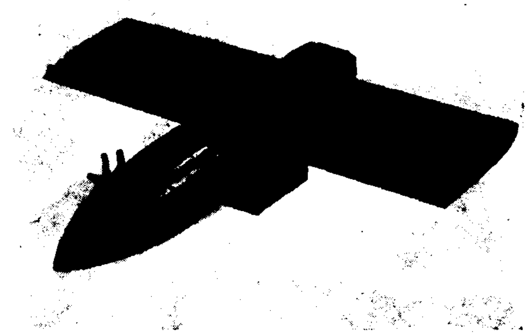

Fig. 85. GB-4 glide bomb with television guidance system.

There are a number of possibilities of positioning the television transmission equipment aboard a missile or a bomb, and this depends on the type of missile, the dimensions of the equipment, and the guidance method.

For example, in the case of the GB-4 glide bomb the equipment was positioned in the following manner: the television camera was suspended from the bottom of the bomb, with the objective forward (during flight the objective was pointed down), and the television transmitter was housed in the tail section of the bomb (Fig. 85). The receiving equipment in the B-17 aircraft was housed in the operator's section of the cockpit. The operator, having guided the bomb toward the target, could control the functioning of the on-board equipment by means of remote control (synchronization, contrast, etc.).

Another example of positioning the on-board television equipment is the method employed in the American "Rok" bomb (Fig. 86). The tele-

vision head in this bomb is positioned in the nose. The control signals received by the radio receiver of the bomb actuated the engines which controlled the position of the ring that is mounted near the tail section of the bomb and functions in the role of a stabilizer. Achieving control by means of this ring, the bomb is guided to a target selected by an operator who is seated before the screen of a television receiver.

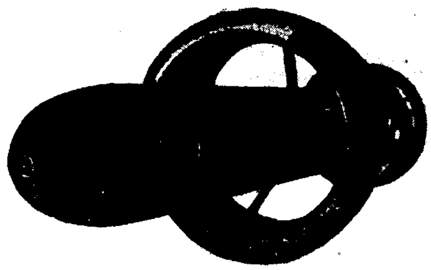

Fig. 86. The "Rok" dive bomb which uses a television guidance system.

The flight trajectory of the object being guided depends on the positioning of the transmission camera. Depending on the guidance method selected, the camera may be oriented in various ways with respect to the axis of the missile or the bomb.

If the missile is being guided against a fixed target so that the flight of the missile, throughout the entire guidance period, follows a straight line, the camera may be installed in the nose of the missile, in a fixed position, and lined up exactly along the axis of the missile. In other guidance cases, in which provision is made for missile or bomb flight along a trajectory that is close to being a parabolic descent (incidence) curve, the camera must be mounted at a certain angle to the longitudinal axis of the missile (bomb) in a fixed position or provision must be made for the gradual shifting of the

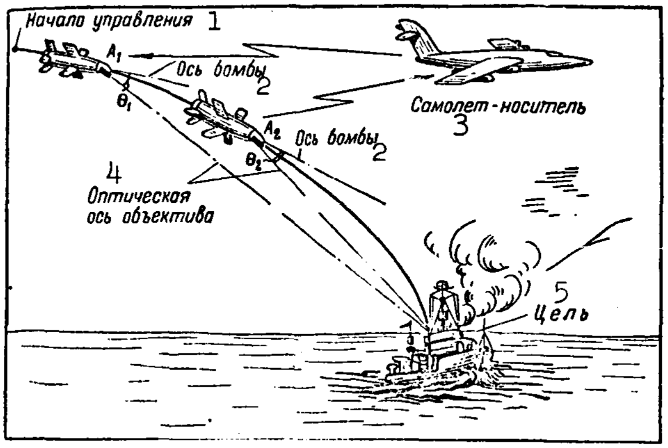

Fig. 87. Guidance of a missile by means of a television tracking head. 1) Start of guidance; 2) bomb axis; 3) carrier aircraft; 4) optical axis of objective; 5) target.

camera by means of a special programmed mechanism (Fig. 87) and this depends on the steepness of the flight trajectory. In the first case, the equipment is simpler, but the target will not be situated directly in the center of the receiving-tube screen throughout the entire guidance period and it will be more difficult for the operator to determine which commands must be given in order to guide the bomb properly to the target. In the second case, the case in which the camera shifts with respect to the body of the missile throughout the entire flight in accordance with changes in the curvature of the trajectory, the operator will have the target in the center of his screen the entire time and the control functions can generally be reduced to slight trajectory corrections.

Guidance by means of a television system may be made more difficult as a result of random missile oscillations, and this produces image oscillation with respect to the center of the screen. To eliminate the harmful effects of missile oscillation during flight, the television camera is stabilized by means of gyroscopes. This method of sta-

bilization offers yet another advantage, i.e., it makes it possible to guide an object over the most advantageous trajectory.

The first simple television systems which operated on a waveband of 3 m and transmitter power of 15 w employed on-board television equipment that weighed approximately 24 kg exclusive of the monitoring installations and the storage batteries which weighed 8 and 15 kg, respectively.

Contemporary improved systems, given comparatively insignificant increases in weight, are equipped with television transmitters of substantially greater power (generally on the 1 m band) and provide the system with an effective range of the order of 300 to 350 km (the "Ring" system).

For purposes of guiding missiles and bombs over great distances, for purposes of dropping these from great altitudes, or because of clouds, combined guidance and monitoring systems are used to make possible the utilization of television-head missiles for ranges up to 500 km.

A television guidance system has the following advantages: the possibility of guidance against targets that are not in the operator's field of view; the possibility of exact guidance to a selected target as a result of improved target visibility with approach to the target; the possibility of selecting the most important target from among a number of near-by targets; freedom of maneuver for the carrier aircraft after ejection of the missile and the possibility of remaining outside of an enemy's range of fire; the possibility of monitoring guidance simultaneously at several stations; and the possibility of transferring missile control from one aircraft to another.

Among the shortcomings of the system we might mention the following: the dependence on weather and illumination, the possibility of an

enemy producing radio interference, and inadequate guidance range, which can be increased only in combination with other systems.

With the appearance of color and three-dimensional television, as well as night-vision instruments, the possibilities of improving television guidance systems increased significantly. The perception of relief in the area of the image may serve to improve guidance accuracy. A color image will enhance better recognition of targets and will make it possible, in a number of cases, to disclose the presence of camouflage. The utilization of electronic-optical converters will make it possible, in a number of cases, to employ this system during darkness.

Television guidance systems may be used for missiles of the "ground-to-ground" class, (against naval and ground targets), and primarily for missiles of the "air-to-ground" class, including conventional and glide guided bombs, torpedoes, and airplane missiles. Television systems have been used by the Americans for purposes of guiding guided bombs during the war in Korea. Combat experience, however, has demonstrated that these systems cannot be adequately protected against interference.

§4. RADIONAVIGATION GUIDANCE SYSTEMS

Radionavigation guidance systems for guided missiles provide for the utilization of known ground radionavigation facilities, with certain changes and improvements which make possible operations in conjunction with the equipment aboard the missile. We have reference here to the fact that the missile is also fitted out with corresponding guidance equipment.

Of the known radionavigation systems used for the guidance of missiles, the hyperbolic and circular systems may be employed without any particular difficulties. The hyperbolic systems generally provide for the flight of a guided object along a curve that is referred to as a

hyperbola. The Loran, Gee, and the Decca systems are included among these. The Shoran, Oboe, etc., systems are included among the circular systems which provide for flight around a given circumference.

Of the hyperbolic systems the Loran and Gee systems are classified as pulsed radionavigation systems. The Decca system is included among those that use continuous radiation and is based on the phase method of measurement. The basic characteristics of these systems are, however, identical.

Of all these systems the Loran system has gained greatest acceptance; let us examine the operation of this system in greater detail. The operating principle of this system is based on the measurement of the difference between the time of the arrival of pulses from two pairs of ground transmission stations whose positions have been established exactly. The geometric locus for which the difference in the time of pulse arrival from two fixed stations is a constant quantity is a hyperbola. There exists a set of curves for each pair of stations for which the difference between the time of pulse arrivals at any point on these curves (or difference in range) from these two stations is constant, i.e., there is an entire family of hyperbolas.

Two families of hyperbolas from two pairs of stations, intersecting in the horizontal plane, form a so-called grid of hyperbolas which is a unique coordinate system. The intersection of two hyperbolas from various families will yield a specific point on the plane, i.e., it will determine the position of the object (Fig. 88). By measuring the difference between the pulse-arrival time from one pair of stations at any instant of time aboard the object being guided, it will be possible to pick out from the entire family that particular hyperbola on which the object is located. We can pick out the hyperbola from the second family of hyperbolas by measuring the difference between the

times of pulse arrival from a second pair of stations. The point of intersection of the selected hyperbolas determines the position of the object. If equipment has been installed aboard the missile to measure the time difference for the pulse arrivals from each pair of stations automatically and if this equipment is capable of comparing this difference with the given time difference, the equipment will be able to bring the object to the given point.

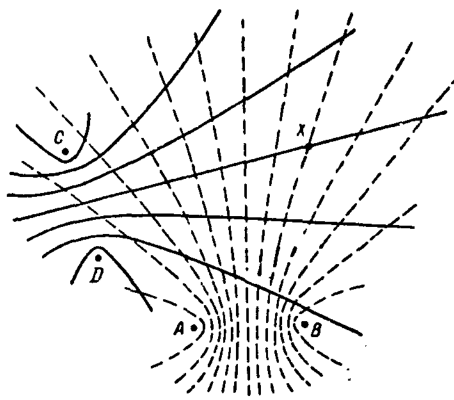

Fig. 88. Family of hyperbolas for two pairs of stations in the hyperbolic radionavigation Loran system: A, B, C, and D) positions of stations; X) position of target determined by intersection of two hyperbolas.

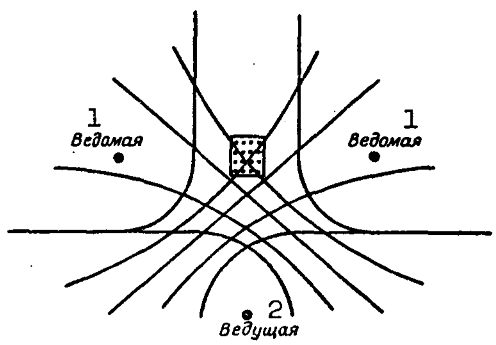

Fig. 89. Position of hyperbolas in the case of three Loran system stations. 1) Slave; 2) master.

In actual practice, it is not two independent pairs of stations

but a total of three stations that is actually used (Fig. 89), and of these one is the master (or the master station) which controls the operation of the two other stations — the slave stations. The master station is equipped with a radio transmitter, and the slave station is equipped with a receiver-transmitter unit. Each slave station retransmits the signals of the master station and is exactly synchronized with the latter; here, in order to ensure, in all cases, the arrival first of the pulses from the master station, and then from the slave station, the latter emits pulses with a constant time lag that is governed by the distance between the stations. In order to distinguish one pair of stations from another, the carrier frequency and the duration of the pulses for various pairs of stations are not the same.

To ensure automatic missile control the on-board equipment must include a receiving installation, a time comparator, and a computer. Since signals are received from each pair of stations, there must be two receiver devices aboard the missile. In order for the signals from all of the stations to be received with a single common antenna, the frequencies of both pairs of stations must be sufficiently close.

The comparator must measure the difference between the pulse-arrival times from each pair of stations automatically and it must compare these. This can be carried out, for example, by automatically causing the pulses of the slave stations to coincide with the corresponding pulses of the master station.

The computer compares the output data from the time comparator against the given data and determines the voltage which controls the yaw channel of the autopilot.

Since radionavigation systems can guide missiles in a two-dimensional coordinate system, altitude control in these systems is generally carried out by means of an altimeter whose output signal is

transmitted to the pitch channel of the autopilot.

Such a system can carry a missile over one of two hyperbolas passing through the target until the second hyperbola is reached. At that instant, the final guidance stage begins (generally homing or diving).

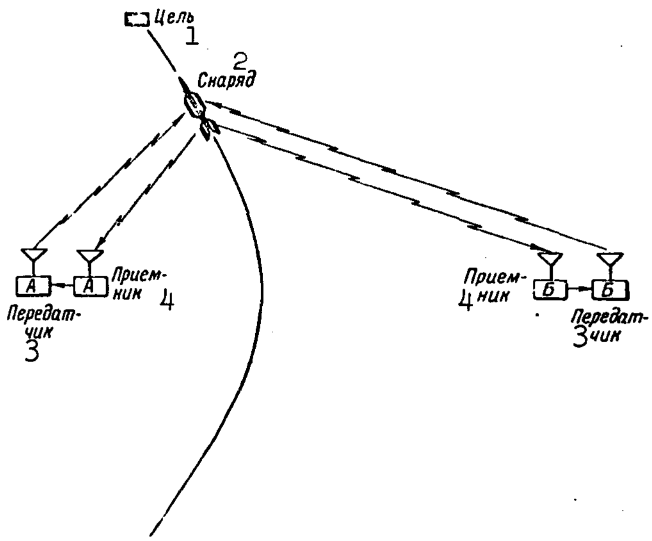

Fig. 90. Guidance of missile by means of hyperbolic radionavigation system for the case of a command transmitter aboard the missile. 1) Target; 2) missile; 3) transmitter; 4) receiver.

Another version of the system is also possible. In this case, the master station (the transmitter) is installed aboard the missile, and two retransmission (slave) stations are situated on the ground (Fig. 90). The signal emitted by the missile transmitter is received by the ground stations, retransmitted on various frequencies, and again picked up by the missile receivers. The received signals are applied to the time comparator and the computer which determine the required data for the control of the missile. In this case the missile will fly along a fully determined hyperbola that passes through the target.

Missile flight along a hyperbola is not the shortest possible flight path and is therefore not economical. In principle, the missile

can be forced to fly any trajectory. The most advantageous missile-flight trajectory is a straight line. However, in flights above the surface of the earth which is spherical, the shortest distance between two points is actually the curved line which corresponds to the great circle.* This curve is referred to as an orthodromic curve. However, for simplicity in determining heading, naval and air navigation make use, generally, of other curves, and these are called loxodromic curves. The loxodromic curve intersects all meridians at the same angle and it is therefore more convenient for purposes of determining heading in comparison to the orthodromic curve which intersects the meridians at various angles, although the loxodromic curve is actually somewhat longer than the orthodromic curve. Therefore, with the utilization of hyperbolic navigation systems, flight along the shortest trajectory is of great practical interest, although it calls for equipment that is somewhat complex.

The principle involved in guidance along a given straight line (more exactly, along an orthodromic curve or a loxodromic curve) consists in the following. The missile must intersect both families of hyperbolas at the initial and final guidance points. The difference between the times of arrival, aboard the missile, for pulses from two pairs of stations at the initial and final guidance points will exhibit a definite relationship which is determined prior to the launching of the missile on a navigational chart according to the known coordinates of these two points. As the missile moves along, the difference between the times of the arrival of the pulses from each pair of stations must change so that the relationship between these differences remains constant and the same throughout the entire period of the flight. With any deviation from the given relationship the time comparator determines the control signal which will force the missile to change heading

so that the required relationship is preserved.

In the case of missile guidance by means of systems which provide for the circle method of navigation, the position of the object is determined by the determination of its position on the circle which passes through the target, and the center of this circle is a fixed point whose coordinates are known. One of the slave stations is situated in the center of the circle, while the command transmitter is situated in the missile (Fig. 91). The distance that has been covered is determined by measuring the time of signal passage, and this distance is compared by the range comparator against the given constant distance. The final resulting signal controls the missile flight along this circle. The other slave station is required to determine the particular point on the circle at which guidance by means of this system ceases and at which the final guidance stage begins.

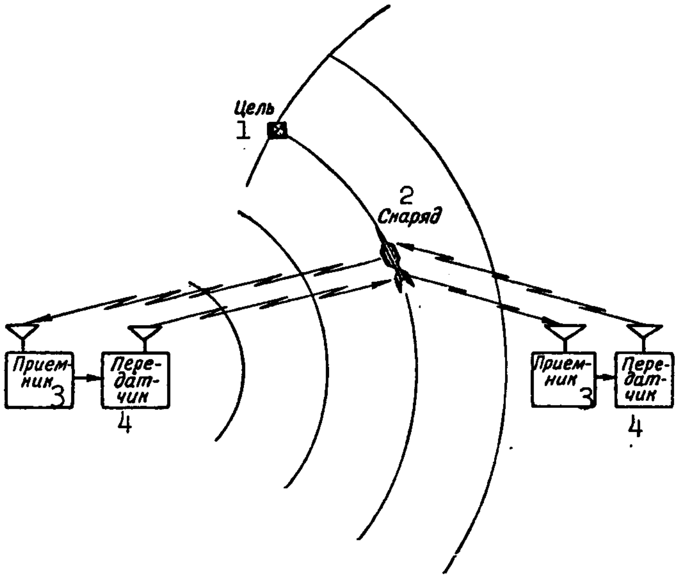

Fig. 91. Guidance of missile by means of circular radionavigation system with installation of command transmitter aboard the missile. 1) Target; 2) missile; 3) receiver; 4) transmitter.

Since it is necessary, as a rule, to receive signals from two

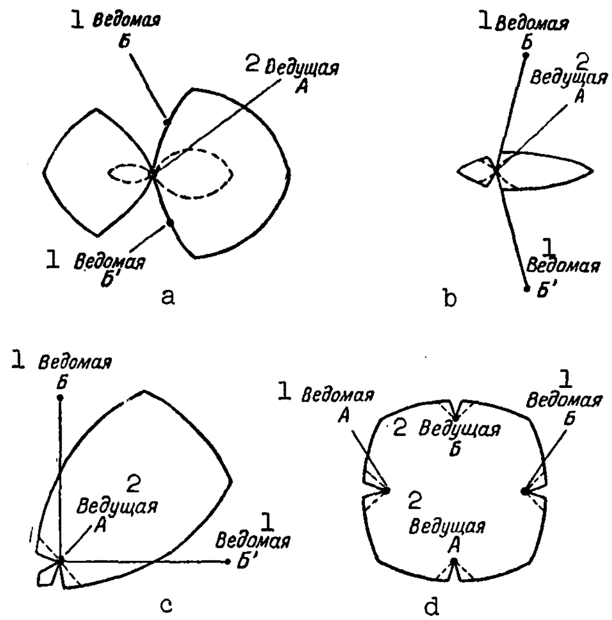

Fig. 92. Configuration of effective guidance zone formed by the radiation patterns of the radionavigation stations, as a function of their number and position: a) for 3 stations, with short base lines; b) for 3 stations, with long base lines; c) for 3 stations, separated through an angle of 90°; d) for 4 stations, positioned in a square. 1) Slave; 2) master.

pairs of stations in order to guide a missile by means of radionavigational systems, a missile may be controlled only in the zone covered by the radiation patterns of all the guidance stations participating in the effort. In terms of configuration and extent this zone depends on the disposition of the stations with respect to one another and the distance between the coupled stations, this distance referred to as the base line (Fig. 92). Given a short base line, the configuration of the zone is close to being that of a circle, and as the base line is increased the zone becomes flatter. In this case, the accuracy in the determination of position at great distances from the base line will be greater, the longer the base line. If two base lines are not situated on a single straight line but at an angle, the encompassed zone

and the accuracy of position determination will increase on the side of the smaller angle. The most suitable sclution for the disposition of the stations is the case in which the base lines are separated by angles ranging between 60° and 90°, at distances somewhat less than the effective range of the stations. In certain cases, should it be necessary to form a zone that is almost square, four stations (two pairs) are used rather than the conventional three stations.

The effective range of the Loran system (Standard Loran), operating on a frequency of 1750, 1850, and 1950 kc, with transmitter pulse power of 70-100 kw, is 960 km during the day and 1920 km at night above a water surface and 480 km during the day and 720-1600 km at night over dry land.

The higher frequencies exhibit a number of advantages (smaller equipment dimensions, less influence exerted by interference), but for long-range navigational systems they are not suitable, since the range of surface-wave propagation in this case rapidly diminishes with distance, and from the standpoint of reception there are the so-called "dead" zones that can be ascribed to waves reflected from the upper layers of the atmosphere, and here reception is completely impossible. Increasing the power of the transmitters to higher frequencies yields virtually no results. Therefore, to increase the effective range of the system, lower frequencies, of the order of 180 kc (low-frequency Loran), were employed, and it was calculated that with a power of 100 kw the range above water would be more than 2400 km both during the day and at night. However, the low frequencies exhibit their own shortcomings and the chief of these is the significant static interference that also serves to restrict the range of the system. To reduce the influence of the latter the passband of the receiver installations is generally narrowed, and this is effective up to a certain limit. The

low-frequency range can be increased by raising the power of the transmitters.

There are also reflected low-frequency waves, but the fluctuations in their intensity are substantially lower. Poorer results in the determination of position are obtained in this case at the critical distances from the ground stations at which the amplitude of the signals from the surface wave is equal to the amplitude of the signals from the reflected waves.

Faultless functioning of the control instruments of the radionavigation guidance systems is most likely during the day at comparatively short distances, when there are no reflected signals, nor any signals from other interfering stations or atmospheric interference. At night, however, the operating conditions become more complicated, since at this time, in addition to the useful signals, there can be reception of numerous signals reflected from the various layers of the ionosphere (Fig. 93). At great distances these signals may predominate over the direct signals from the stations. There are cases in which signals of rather great amplitude are received from a repeatedly reflected wave (from the lower E layer of the ionosphere, then from the earth, and again from the E layer). Moreover, in certain regions, particularly in the equatorial zone, there are powerful atmospheric discharges which disturb the functioning of the system. All of these forms of interference reduce the operational reliability of the radionavigational guidance systems and they result in a reduction of the region of stable system operation.

Hyperbolic navigational systems exhibit low guidance accuracy as a result of which they can be used either for the guidance of missiles over large areas or in conjunction with other systems that provide for more exact final guidance.

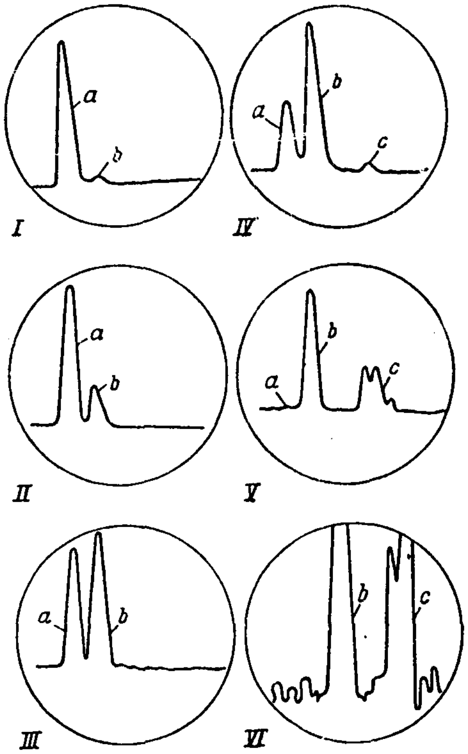

Fig. 93. Types of signals received in pulse radionavigation systems, depending on time of day: a) surface signal; b) signal reflected from E layer; c) signal reflected from E layer, and then from surface of earth, and again from E layer; I) at 1500 hours; II) at 1600 hours; III) at 1700 hours; IV) at 1800 hours; V) at 1900 hours; VI) at 2000 hours.

The guidance accuracy of these systems is a function of the accuracy with which the coordinates of the ground stations and the target are determined, and it is also a function of the precision with which the signals are delayed during retransmission by the slave stations; in addition, the guidance accuracy of these systems depends on the direction with respect to the base line and on the angles at which the lines of the two families of hyperbolas intersect.

Depending on the direction relative to the base line (the line

which connects the command transmitter and the slave station), the accuracy of determining the position is expressed in the following practical values: at distances of 500 to 1200 miles from the base line at an angle of about 30° from the normal for 95% of the measurements, 0.9% of the distance; at an angle of about 60°, greater by a factor of two; beyond the limits of 60°, accuracy drops sharply, since at these points the position of the hyperbolas changes drastically, even with slight changes in the difference between the distances. As a result the ground stations must necessarily be positioned so that the region in which the target is located is reliably covered by the radiation pattern of the station and so that the target, if at all possible, is kept close to a line perpendicular to the base line.

The required guidance accuracy depends primarily on the dimensions of the target, the effective radius of the explosive charge, and on knowledge of the exact target coordinates. It is also necessary to bear in mind that the lines of the hyperbolic system themselves are not exactly hyperbolas (because the earth has the shape of a flattened spheroid), and this is taken into consideration during the preparation of the navigational charts that are used for guidance over great distances.

Radionavigational systems may be used primarily for the guidance of medium- and long-range airplane missiles. In the case of comparatively short-range systems, in order to be able to position the launching sites at the maximum possible distance from the target, the missile can be made to fly along an unguided heading or by means of some other guidance system, and then as the missile enters the effective zone of the radionavigational system, the latter can be employed to guide the missile to the region in which the target is situated, subsequent to which a system of final short-range guidance may take over

to guide the missile exactly to the target.

An advantage of the radionavigational systems is the possibility of utilizing an unlimited number of missiles simultaneously, launching these from many points (launching sites) without any coordination. Among the shortcomings of the system is the dependence on conditions of radiowave propagation, the comparatively low guidance accuracy, the possibility of using the systems only against targets that remain stationary throughout the entire period of missile flight, and the susceptibility to the effects of atmospheric interference and the interference produced by an opponent.

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199	The line of intersection between the sphere and the plane passing through the center of this sphere is designated as the great circle.

Chapter 8

AUTONOMOUS CONTROL SYSTEMS

§1. MAGNETOMETRIC GUIDANCE SYSTEM

The operating principle of a magnetometric system involves the continuous measurement of those elements of the earth's magnetic field, which characterize the position of a missile in space, and a comparison of these elements with those values given and established by program devices. With a deviation in the measured quantities from those that have been given, an error signal is produced, and this signal, after conversion, is transmitted to the autopilot and controls the missile in the corresponding planes. A magnetometric system, just as the other autonomous control systems, is included among the programmed guidance systems and is used for the guidance of long-range missiles.

The magnetic field of the earth encompasses the entire terrestrial globe and with its elements forms a specific coordinate system that is, in some degree, similar to the geographic coordinate system. Therefore, the measurement of the elements of the earth's magnetic field makes it possible to determine the position of an object at any point on the globe.

The vector of field intensity and its components serve as the characteristics of the earth's magnetic field, or for that matter, of any magnetic field. The total field strength (the field-strength vector) lies in the vertical plane and this plane is referred to as the plane of the magnetic meridian. The distribution of these magnetic meridians is somewhat reminiscent of the distribution of the geographic

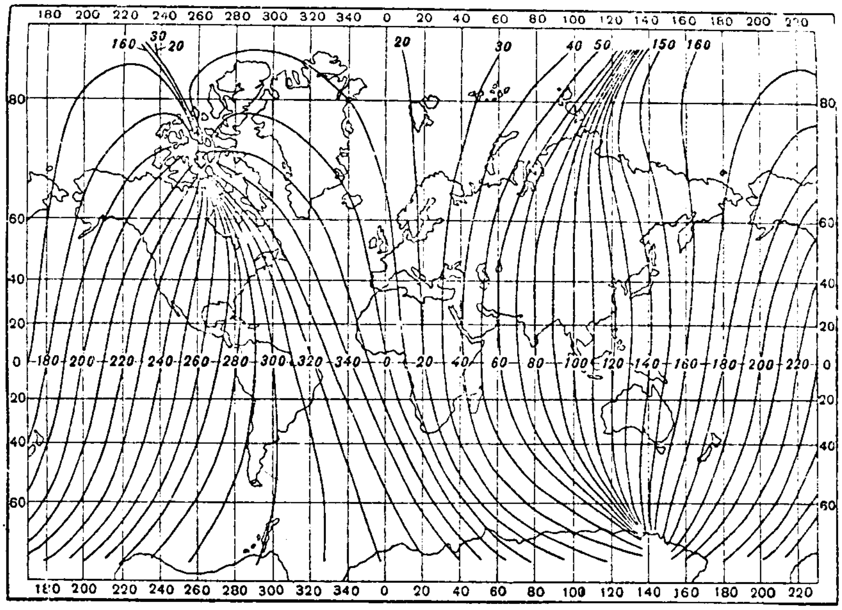

Fig. 94. Magnetic meridians characterizing the course of total intensity of the earth's magnetic field.

meridians (Fig. 94). The projection of the total field intensity to a horizontal plane is referred to as the horizontal component H and when projected onto the vertical axis it is referred to as the vertical component Z of field strength. The angle between the horizontal component and the geographic meridian is referred to as magnetic declination D, and the angle between the horizontal component and the total field strength is referred to as magnetic dip I.

Moreover, if the horizontal component of the field strength were expanded over the axes of the geographic coordinate system, we would obtain an additional two components — the northern component X and the eastern component Y.

All of the above-enumerated quantities are referred to as elements of terrestrial magnetism. However, in order to obtain a sufficiently complete characteristic of the terrestrial magnetic field at any point on the earth's surface it is necessary to know three basic magnitudes:

the horizontal component H, the declination D, and the dip I. These magnitudes may be measured by magnetometers.

The magnetic field of the earth and its elements are not uniformly distributed over the surface of the globe. To obtain a clearer picture of the distribution of all or some of the elements we make use of the graphic method of representing the magnetic field, setting up special charts on which isolines are plotted, i.e., the curves which connect the points with identical values of a given element on the chart. Thus, for example, the curves which connect the points of identical declination are called isogons, and the curves which connect points of identical dip are referred to as isoclines; the curves which connect identical horizontal (vertical) components are referred to as isodynamic curves of the horizontal (vertical) components (Figs. 95 and 96).

Magnetic charts are prepared on the basis of materials gathered through magnetic readings of individual regions, nations, and finally, for the entire terrestrial globe. In the latter case, they are called universal charts. These charts present a clear picture of the qualitative and quantitative aspects of the earth's magnetic field as a whole or for individual regions of particular interest.

We can see from an examination of universal magnetic charts that the isolines of the elements of terrestrial magnetism exhibit a definite quantitative relationship in their distribution. For example, the isogons emanating at one point of the globe converge at another almost completely opposite point, reminding one of the course of the meridians. The eastern portion of the Asian continent is an exception, since the isogons close on themselves here (Fig. 97).

There are two isogons for which the magnetic declination is equal to zero. These correspond to the 0° and 180° meridians and are referred

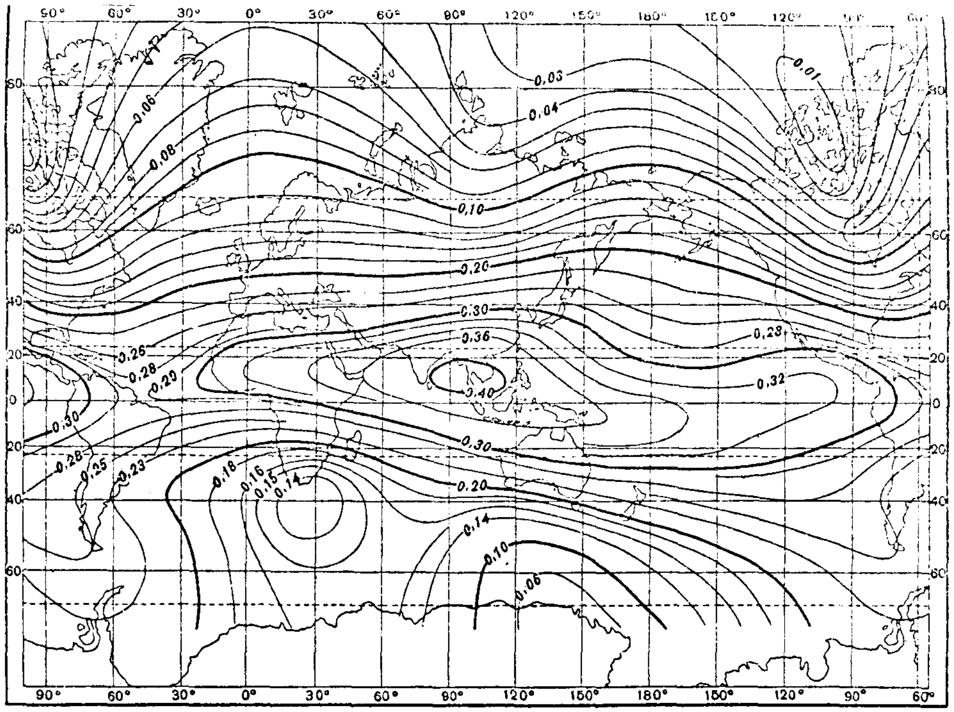

Fig. 95. Isodynamic curves of the horizontal component of the field strength of the earth's magnetic field.

to as agonic lines. The isogons in the regions of the geographic poles do not converge at two but at four points: at the two geographic and the two magnetic poles (Fig. 98). This is explained by the fact that at the magnetic pole where the horizontal component is equal to zero the concept of the magnetic meridian and declination loses all significance; at the geographic pole declination with respect to the geographic meridian, which is absent in this case, becomes indefinable.

In the passage from the northern magnetic pole to the southern magnetic pole the horizontal component initially rises from zero to a certain maximum, and then again diminishes to zero.

The isoclines exhibit a smoother and somewhat more regular course; these isoclines are a series of parallel curves that are extended in the latitudinal direction. The zero isocline, referred to as the magnetic equator, passes around the globe and is situated close to the

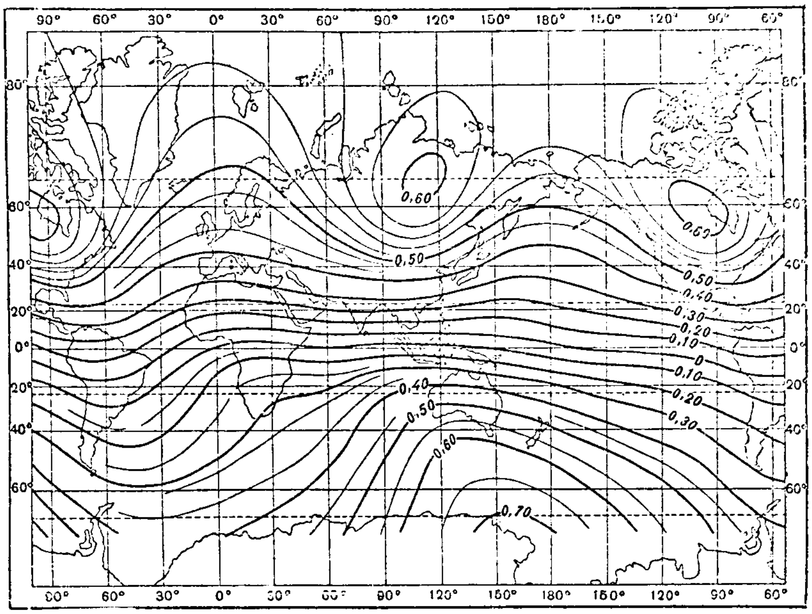

Fig. 96. Isodynamic curves of the vertical component of the intensity of the terrestrial field.

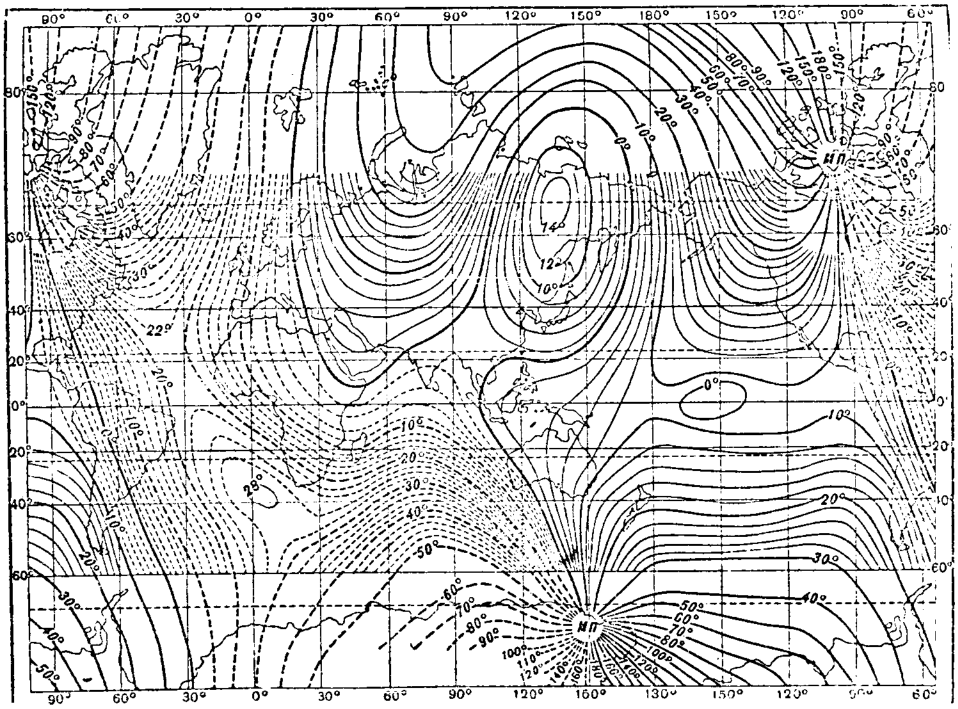

Fig. 97. Isogons connecting points of identical declination.

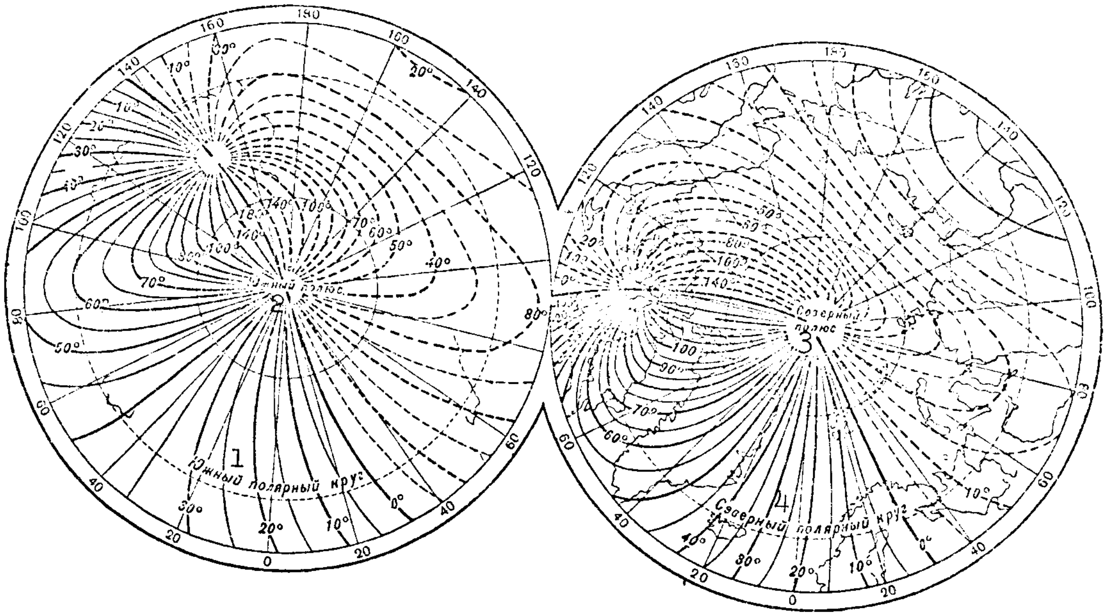

Fig. 98. Isogons in the regions of the geographic poles. 1) Antarctic circle; 2) South Pole; 3) North Pole; 4) Arctic circle.

geographic equator.

It is possible to observe in an examination of the magnetic charts of individual regions that the regularity of the isolines is markedly disrupted at certain points (it is said that anomalies exist), and the isolines assume a thoroughly entangled appearance. This is explained by the nonuniformity of the structure of the earth's shell, in particular of the earth's crust which, exhibiting a variety of magnetic properties, is variously magnetized at various points.

As is demonstrated by observation, not a single one of the elements of terrestrial magnetism remains constant and each of them changes in magnitude hourly, yearly, and during the course of extremely prolonged periods of time. Such changes have been designated as variations in the elements of terrestrial magnetism. The electrical currents in the upper layers of the atmosphere (magnetic storms) are responsible for the rapid variations, whereas the slow or protracted variations depend on processes taking place within the earth itself.

Since the elements of terrestrial magnetism do not remain constant with respect to time, but change continuously, magnetic charts are prepared regularly after certain definite intervals of time have passed (usually, after a lapse of 5 years). The period for which a particular chart is prepared is referred to as an epoch.

For purposes of guiding missiles by means of systems making use of the terrestrial magnetic field we require instruments which would be capable of measuring automatically the individual elements of terrestrial magnetism and would be capable of producing information that is suitable for the development of control signals.

One such instrument is the magnetic compass which must be mounted so that it can move freely in the horizontal plane. The indicator of the compass seeks constantly to maintain its position in the plane of the magnetic meridian and if the magnetic bearing to the target is known, an error signal will be produced in the system for any deviation on the part of the missile from a trajectory other than the given heading, and this error signal will compel the missile to turn so that the error vanishes. Such a compass was used as an element of the guidance system in the V-1 missile in which it made it possible to produce a control signal which corrected the functioning of the autopilot with respect to the azimuth.

If the compass were to be mounted in such a manner that it had two degrees of freedom, the compass would be capable of measuring both the declination and the dip. If, moreover, these magnitudes were read off from a magnetic chart or were calculated and recorded onto a magnetic tape and then, by means of special equipment, compared with the quantities measured during the flight, the resulting signal (in the form of an error signal) could be utilized for the guidance of the missile along the required trajectory.

As one of the elements of the guidance system we can use a simple DC current generator for which the magnetic field of the earth could serve as the exciting magnetic field. If the axis of rotation of the armature of such a generator were mounted in the direction of the total field strength, there would be a voltage equal to zero at the output clamps of the generator. With deflection of the generator axis from the direction of the field-strength vector there would be some voltage at the output. Such an instrument, referred to as a dipping compass, can be used to control a missile along the line of total intensity of the terrestrial magnetic field. By using the appropriate program mechanism the missile can be guided to the target.

There is an entire series of similar instruments that have been developed for the measurement of the elements of terrestrial magnetism; we have reference to such instruments as magnetic theodolites (for the measurement of the horizontal component, declination, dip), magnetometers, gyromagnetic compasses, etc., which, when adapted for operations aboard a missile, may be used in a magnetometric system of guidance. Altitude control may be carried out by means of an altimeter.

A shortcoming of the magnetometric guidance system is its low accuracy as a result of:

1) the nonuniformity of the distribution of the magnetic field over the surface of the earth (anomaly);

2) the continuous change in the total field intensity of the magnetic field: daily, annually, and random (magnetic storms).

In view of this, the magnetometric guidance system in its pure form encounters significant difficulties from the standpoint of utilization and it may be used either for the guidance of a missile against a target that covers a large area or it may be used in combination with some other system of final and more exact guidance to a

target.

The advantages of the system are the following: the comparative simplicity and the relatively high resistance to interference.

§2. INERTIAL GUIDANCE SYSTEM

Another, more difficult example of an autonomous guidance system used for missiles of various ranges, including long range, is the so-called inertial guidance system.

The inertial guidance system is based on the law of mechanics which states that any change in the motion of a body under the action of various forces is accompanied by acceleration. If the acceleration in various directions were measured in an arbitrarily moving body and if these accelerations were integrated twice it would be possible to calculate the deviation of this body from a straight-line trajectory in any of the directions in which the measurement was carried out. This principle is employed in the inertial system.

A typical inertial system used for the control of missiles provides for the installation (aboard the missile) of several accelerometers which measure acceleration in various planes. The measured accelerations are transmitted in the form of voltages (obtained from the accelerometers) to two series connected integrators of which the first calculates the velocity on the basis of the acceleration data and the second determines the course of the missile in the corresponding direction on the basis of the velocity data (Fig. 99). Thus, by means of these instruments it is possible to determine the lateral deviations of the missile from the given trajectory and the course traveled by the missile.

In the case of random deviations of the missile from the given trajectory, a signal proportional to the lateral deviation is transmitted to the autopilot which acts on the control units and corrects

the missile trajectory. In order for the inertial control system to be able to bring the missile to the target it is necessary for the system to be able to determine exactly the position of the missile with respect to the earth's surface at any instant of the flight and to compare this position with the position given by the program device, and in the case of the appearance of an error signal, to correct the flight trajectory prior to the arrival of the missile at the final guidance point. For this, it is first of all necessary to know the exact coordinates of the launching site and the position of the target.

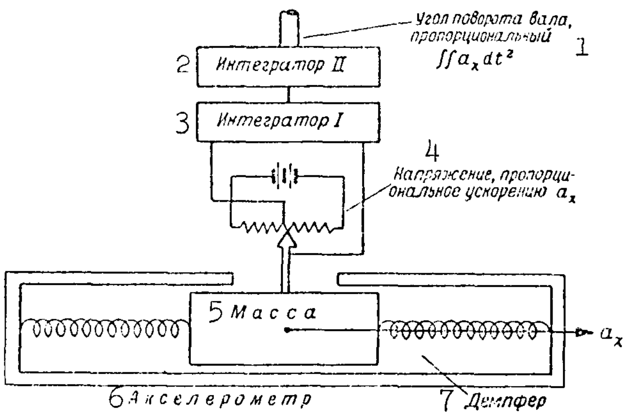

Fig. 99. The principle of calculating the course traveled and determining the lateral deviations in an inertial guidance system by means of accelerometers and integrators. 1) Angle of shaft rotation, proportional $\int\int a_x dt^2$; 2) integrator II; 3) integrator I; 4) voltage proportional to acceleration a_x; 5) mass; 6) accelerometer; 7) damper.

In order to be able to determine exactly (aboard the missile) the position of a missile with respect to the earth's surface in the case of long-range missile flights, it is first of all necessary to take into consideration the effect of a variety of factors on the missile's trajectory, and we have reference here to such factors as the rotation of the earth, etc. For this purpose it is necessary to set up (aboard

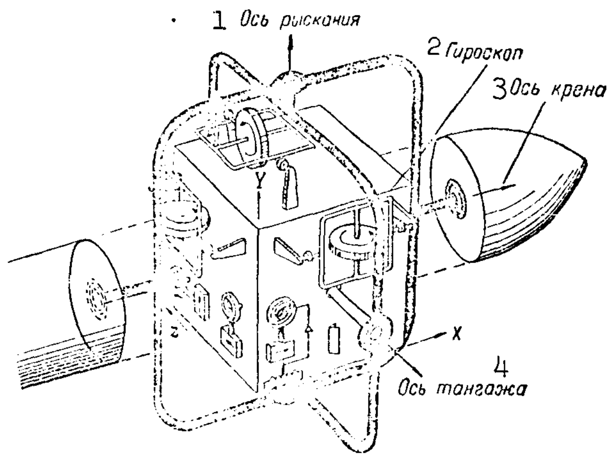

Fig. 100. Principle of platform stabilization by means of gyroscopes. 1) Yaw axis; 2) gyroscope; 3) roll axis; 4) pitch axis.

the missile) a reference system of coordinates that is fixed (inertial) with respect to outer space, and this system is theoretically regarded as the most exact coordinate system. Such an inertial system of coordinates can, in actual practice, be set up on the principle of utilizing the inertial properties of gyroscopes which cause the axis of a gyroscope, regardless of the maneuvers executed by a missile, to seek to remain in a fixed position with respect to outer space. Thus, a gyrostabilized platform (Fig. 100) whose stabilization exactness must be extremely high, can serve aboard the missile as the coordinate system with respect to which it is possible to carry out an exact calculation of all the elements of motion.

The inertial guidance system at this stage of its development consists of the following basic elements:

1) accelerometers, for the measurement of missile acceleration during flight;

2) gyroscopes, for the creation aboard the missile of a stabilized platform to serve as a reference system of coordinates;

3) computers, to calculate heading, distance traversed, to account for the required corrections, and for determination of the final guidance point.

The accelerometers are the most important parts of the inertial system. Depending on their designation, they may either be linear or angular.

Linear accelerometers measure linear accelerations which, for example, after double integration, make it possible to determine the lateral deviations of the missile and the distance covered by the missile. In certain control systems, with the exception of the measurement of linear quantities, it is necessary to measure the angular velocity or angular acceleration of the missile. In such cases angular accelerometers are used.

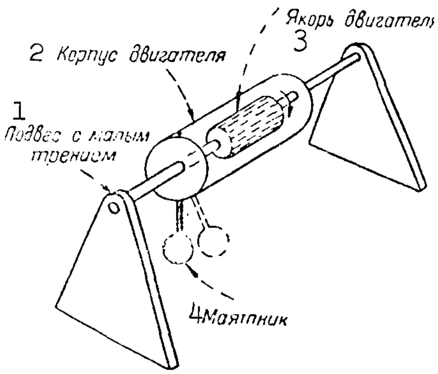

Fig. 101. Linear accelerometer with "electric spring." 1) Low-friction suspension; 2) motor frame; 3) motor armature; 4) pendulum.

The simplest linear accelerometer may be made in the form of a mass that is contained on two sides by means of springs (see Fig. 99). However, the measurement accuracy in such accelerometers is limited by the friction in the bearings and by phenomena of residual deformation in the springs. The accuracy of the accelerometer may be increased by

replacing the mechanical springs with "electrical springs." The action of an accelerometer with an "electrical spring" is based on the operating principle of a DC electric motor. Such an accelerometer consists of a pendulum fastened to the outer shell of the motor, with the shell suspended on bearings which produce little friction (Fig. 101). As linear accelerations act on this instrument the pendulum, together with the outer shell of the electric motor, turns through a certain angle. A voltage corresponding to the polarity is transmitted to the armature of the motor and this produces an opposite moment which will seek to return the shell to its former position. The magnitude of the applied voltage, adequate to turn the shell and the pendulum to the initial position, will be proportional to the linear acceleration applied to the accelerometer. Given small angles of rotation, such an accelerometer reacts only to linear acceleration and is not subject to the undesired effect of the acceleration of the force of gravity. The measurement accuracy of such an accelerometer is of the order of $5 \times \times 10^{-6}$ g.

Similar more improved types of linear accelerometers are being developed.

In order to take into consideration accurately the lateral deviations of the missile and the distance that has been covered it is necessary for the linear accelerometers to neglect the gravitational components (acceleration produced by the forces of terrestrial gravitation). For this purpose the accelerometers must be mounted on a stabilized platform that is kept strictly in a horizontal position with respect to the earth throughout the period of missile flight. The best indicator of the correct position of the platform with the accelerometers is provided by a comparison of the position of the platform with the direction of the force of terrestrial gravitation which, for any

point on the terrestrial surface, in first approximation, is always perpendicular to the plane of the horizon; this indicator is generally referred to as the vertical. The direction of the vertical varies at each point on the terrestrial surface.

In order for the platform with the accelerometers to remain in a horizontal position the entire time, it must turn with respect to the stabilized platform of the missile as the missile moves (this is a fixed system of coordinates), so that it is perpendicular to the new local vertical at any instant of time. Provision must therefore be made for a servodrive which would turn the platform, using the covered-distance feedback from the accelerometer, expressed in terms of the angle between the initial and the instantaneous vertical (the covered distance, divided by the earth's radius).

Since a missile may be launched virtually in any direction with respect to the launching site, for simplicity of calculations it is expedient to express the motion of the missile in a conventional system of terrestrial coordinates in terms of longitude and latitude. Therefore, in an inertial system two accelerometers, measuring acceleration, are generally installed at right angles to each other in two mutually perpendicular directions on the accelerometer platform for purposes of measuring the elements of missile motion: one accelerometer measures the direction "north-south," and the other measures the direction "east-west" (Fig. 102).

These accelerometers perform several functions in the inertial system:

1) they make it possible, through the autopilot, to execute corrections in the missile trajectory in the case of random deviations;

2) they provide initial data for the calculation, by means of the computer, of the path covered by the missile;

3) they serve as feedback elements required for the maintenance of the accelerometer platform in a horizontal position.

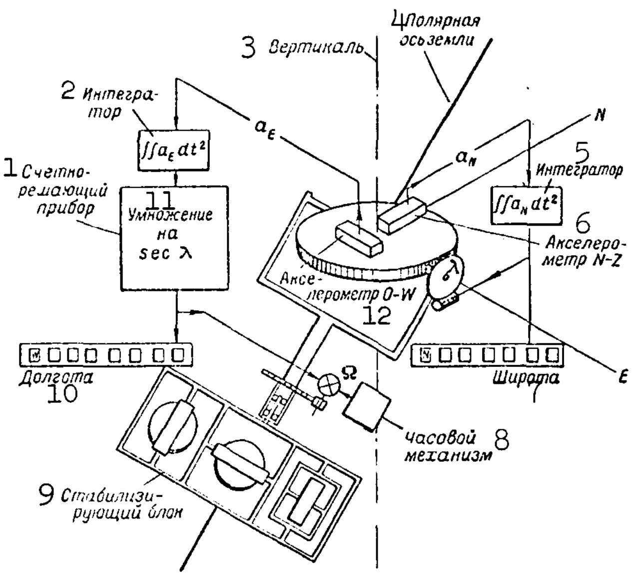

Fig. 102. Elements making up the inertial guidance system. 1) Computer; 2) integrator; 3) vertical; 4) polar axis of the earth; 5) integrator; 6) accelerometer N-S; 7) latitude; 8) clockwork; 9) stabilizing unit; 10) longitude; 11) multiplication by sec λ; 12) accelerometer O-W [east-west].

All of these functions are carried out independently of each other by the accelerometers through two independent channels (longitude and latitude).

Missile altitude control, depending on the complexity of the inertial system and the nature of the given trajectory, can be achieved either by means of an altimeter or by means of a third accelerometer which is installed on the same platform and perpendicular to the first two (in the direction of the vertical) to detect missile acceleration with change in flight altitude (see Fig. 100).

The diagram of such a system, consisting of the above-enumerated basic elements, is presented in Fig. 102.

Any changes in flight conditions not provided for in the program (force of wind, load due to wind gusts, change in engine power, etc.) produce a reaction on the part of the accelerometers in such a system, thus making it possible to obtain an error signal and a force, proportional to this error signal, acting on the missile-control units.

For purposes of maintaining the accelerometer platform in a horizontal position, a special tracking system must turn the platform with the same angular velocity at which the missile is flying with respect to the center of the earth. In accordance with the above-mentioned disposition of the accelerometers, the rotation of the platform during missile motion in an arbitrary direction is also achieved through two channels: longitude and latitude. However, this is not yet enough to maintain the platform in a horizontal position. It is still necessary to take into consideration the effect produced by the rotation of the earth.

If the missile is moving, for example, along a meridian, acceleration with respect to longitude is absent in this case and the accelerometer platform, as it would seem at first glance, must be rotated by the drive mechanism of only the single channel connected to the latitude accelerometer (Fig. 103). However, during the period of missile flight the terrestrial coordinate system will turn with respect to the spatial coordinate system at an angular velocity that is equal to the angular velocity of terrestrial rotation, and given the fact that there is no compensation the accelerometer platform will not remain in a horizontal position with respect to longitude. In order to avoid this, the inertial control system must include a clockwork mechanism which, by means of a corresponding drive mechanism, would rotate the accelerometer platform in the longitudinal direction at an angular velocity of 15 deg/hr to compensate the effect of terrestrial

rotation. Such compensation is required during missile flight in any direction.

In this case it is necessary to take into consideration that the linear distance covered by the missile in the "east-west" direction, corresponding to the given longitudinal angle, is a function of the latitude of the position. Therefore, it is necessary to introduce a latitude correction (multiplication by sec λ, i.e., the secant of the latitude angle) into the output signal of the longitude-channel accelerometer integrator, prior to the transmission of this signal to the drive mechanism which rotates the accelerometer platform.

After having taken into consideration the corrections for the effect of terrestrial rotation, we find that the accelerometer platform will theoretically be in a horizontal position with respect to the surface of the earth. However, the accuracy of the tracking system (the drive mechanism) cannot be adequately high and therefore its operation must be continuously corrected by means of an instantaneous-vertical indicator.

Consequently, a sensitive instrument which could indicate the true vertical at any point of the flight trajectory and continuously indicate its instantaneous position must be installed on the missile. The known vertical sensing elements – the gyrovertical and gyrohorizon – offer inadequate accuracy, since a moving missile is constantly subjected to all possible types of accelerations as a result of random deviations or preset maneuvers, and these accelerations almost always yield a horizontal component that affects the accuracy of vertical indications. Thus the vertical indication aboard the missile may not be accurate, since in this case it will represent the resultant vector that is the sum of two forms of acceleration: of the force of terrestrial gravitation and of horizontal components. Such an apparent ver-

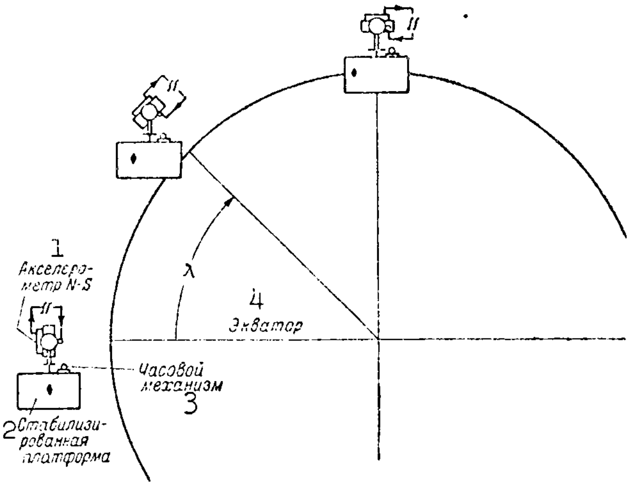

Fig. 103. Change in the mutual position of the accelerometer platform with respect to the gyrostabilized platform during missile flight along a meridian, as a result of the functioning of the system through the latitude channel. 1) Accelerometer N-S; 2) stabilized platform; 3) clockwork mechanism; 4) equator.

tical will be inclined with respect to the true vertical. An error of one minute of arc in the determination of the vertical results in an error of one mile in the determination of the position of the missile. It is therefore necessary to have an instantaneous-vertical indicator on the missile that is capable of constantly indicating the true vertical or, at least, the position of the vertical with minimum error.

The indication of the true local vertical is among the most complex and important of the elements of the inertial guidance system. Investigations have shown that an error in the indication of the true vertical has a tendency to oscillate at a definite frequency. The period of these oscillations is determined by the following equation, which is the equation for the pendulum,

$$T = 2\pi\sqrt{\frac{l}{g}} = 2\pi\sqrt{\frac{R}{g}} = 84{,}4\,\mathrm{min},$$

where R is the radius of the earth.

This is the period that will be exhibited by a physical pendulum suspended on a weightless thread at the surface of the earth so that the mass of the pendulum will be situated in the center of the earth. Such a pendulum experiences no horizontal accelerations.

In principle, any pendulum exhibiting an oscillatory period of 84.4 minutes will be insensitive to horizontal accelerations. Therefore, a pendulum with such a period would be simple and an effective vertical indicator; however, the utilization of pendulums is not practical.

Gyroscopes with a large angular moment are used in the place of pendulums; these gyroscopes, as was demonstrated by the German physicist Schuler, could be adjusted for the critical pendulum ratio and would exhibit the required periodicity. Such gyroscopes will also be insensitive to the errors produced by horizontal accelerations. In certain systems, however, the same thing can be achieved by means of computers through regulation of their amplification so as to achieve synthetically the required oscillatory period.

As in similar systems, computers are required for automatic missile control on the basis of the information received from all of the navigational instruments of the system, as well as to calculate and offset the accelerations produced by external forces.

The computers must incorporate integrators and various similar elements intended for the performance of definite mathematical operations (primarily, trigonometric) and the conversion of the output data from the instruments into the data of the corresponding coordinate system.

All of the given conditions (acceleration during take-off, change in flight trajectory, etc.) are plotted on the program graph (or recorded on magnetic tape) and fed into the computer.

After having taken into consideration the curvature of the earth and after the execution of an entire series of trigonometric calculations, the computer can determine the instantaneous coordinates of the missile (latitude and longitude of position), heading, covered distance, and the distance which the missile has yet to cover. The resulting data are compared with those given in the program device, and any deviation from the given heading is corrected by means of autopilot servomechanisms, which turn the control surfaces in the required direction.

As soon as all of the instruments of the inertial guidance system required for missile guidance have been installed aboard the missile, it becomes necessary to select a point of orientation for the introduction of the initial data of the reference coordinate system (stabilized with respect to the space of the platform). The polar axis of the earth is generally selected as such a guide line (point of orientation) in an inertial system.

The guidance heading for a missile may be determined if the coordinates of the initial and final guidance points are known, i.e., if the astronomical latitude of these points is known (the angle between the vertical and the equatorial plane) and if the longitudinal difference between them is known.

The accuracy of the inertial system is a function of the extent to which the system is capable of fully and exactly offsetting the influence of the various forces acting on the missile (we have reference here to consideration of the various correction factors), and it is also a function of the class of instrument accuracy that is employed for the on-board equipment of this system.

For more exact missile guidance it is necessary for the inertial system to introduce correction factors by means of computer installa-

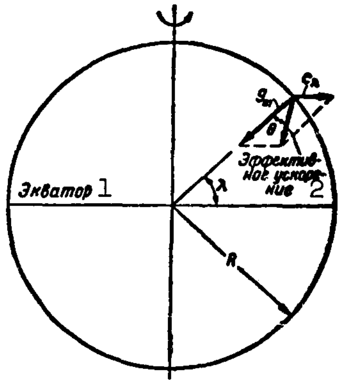

Fig. 104. Effective acceleration due to terrestrial gravitation: g_T) acceleration due to the attraction of the earth's mass; c_λ) acceleration caused by centrifugal force as a result of terrestrial rotation. 1) Equator; 2) effective acceleration.

tions so that it is possible to take into consideration the effect of such external forces as the horizontal component of acceleration that is produced by the rotation of the earth and the anomalies of the terrestrial surface; in addition, these correction factors must take into consideration the effect of the Coriolis acceleration that is produced as a result of the rotation of the earth with respect to the fixed coordinate system.

It is also necessary to bear in mind that exact indication of the true vertical on the missile is a function not only of the exactness with which the measurement of the direction of the vector of terrestrial-gravitation acceleration is measured, but also of the exactness with which the direction of this vector reflects the direction of the true vertical, i.e., how exactly the acceleration vector coincides with the true vertical with respect to direction.

The effective acceleration of gravitational attraction is in fact the sum of two vectors: the acceleration of the attraction of the earth's mass and the acceleration produced by centrifugal force as a result of terrestrial gravitation, i.e., equal to $\Omega^2 R \cos \lambda$, where Ω is the angular velocity of terrestrial rotation; R is the radius of the earth; and λ is the latitude of position.

It is clear that the vector of the centrifugal force is directed perpendicularly to the axis of terrestrial rotation, and its magnitude is equal to zero at the pole and equal to its maximum at the equator.

At all latitudes with the exception of the poles and the equator the centrifugal force yields the horizontal component which, when added to the force of terrestrial gravitation, yields the deflection in the direction of the apparent vertical from the true vertical (Fig. 104). At the equator this force attains its greatest magnitude, but with respect to direction it is directly opposed to the force of terrestrial attraction and therefore has no effect on the direction of the resultant vector of the force of terrestrial gravitation, i.e., at the equator the true and effective (apparent) verticals are situated on one and the same straight line.

The angle between the apparent and true verticals is the error which must be offset. The deviation in the apparent vertical from the true vertical is proportional to $\Omega^2 R \sin 2\lambda$ and attains its maximum at a latitude of 45°, where it attains a magnitude of about 11 minutes of arc. The compensation can be introduced by calculating the voltage shift for the "north-south" accelerometer, this being proportional to $\sin 2\lambda$.

Anomalies in shape and in the surface of the earth, such as the flattening of the earth, mountain ranges, etc., influence the magnitude of the angle by which the apparent vertical is deflected from the true vertical. We know that the radius of the earth that passes through the poles is equal to 6356.863 km, whereas the radius in the plane of the equator is equal to 6378.245 km. The flattening of the earth amounts to 0.335% (Fig. 105). As a result of the flattening of the earth, the gravitational acceleration at the poles must be lower than at the equator. However, as a result of the presence of centrifugal force, due to the rotation of the earth, the effective gravitational acceleration in actual fact amounts to: 9.78046 m/sec^2 at the equator, and 9.83223 m/sec^2 at the poles.

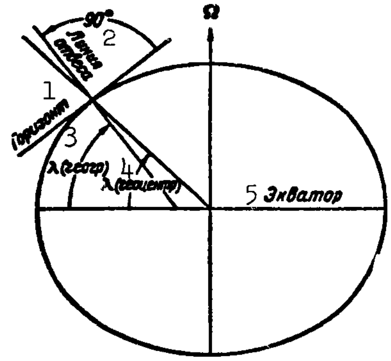

Fig. 105. Effect of the flattening of the earth on the direction of the true vertical. 1) Horizon; 2) perpendicular; 3) λ (geographic); 4) λ (geocentric); 5) equator.

Anomalies in the earth's surface are taken into consideration either by means of formulas or by means of navigational charts, and the correction factors to offset the effect of these anomalies are sometimes advantageously introduced, particularly in the case of guidance for long-range missiles.

A missile flying a straight line (more exactly, at constant altitude along an orthodromic curve) at constant velocity with respect to the earth continuously changes both direction of velocity in space and the magnitude of its tangential component with respect to the fixed spatial coordinate system. Since the missile is moving in a rotating coordinate system with respect to a fixed system of coordinates it experiences the so-called Coriolis acceleration which can deflect a missile from its given trajectory. The magnitude of this deflection depends basically on the latitude of the area and the duration of missile flight (Fig. 106).

In the case of a missile flying at a constant altitude the horizontal component of the Coriolis acceleration becomes extremely important:

$$a_{o} = 2\Omega V \sin\lambda,$$

where V is the horizontal velocity of the missile. If the accelerometers are not compensated proportionately to this expression, the accelerometers of a missile flying in the northern hemisphere directly south along a meridian will show the eastern component of acceleration which, in fact, does not exist under conditions of flight with respect to a terrestrial system of coordinates. To offset this error, the

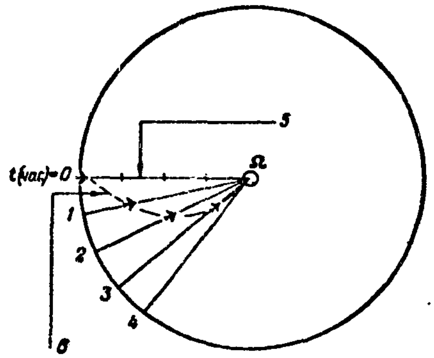

Fig. 106. Influence of the Coriolis effect on the trajectory of a moving object (the missile is moving from the equator to the north pole): 1, 2, 3, and 4) rotation of the calculated missile trajectory during flight time; 5) calculated missile trajectory with respect to the earth; 6) actual trajectory of object in inertial space; Ω) angular velocity of terrestrial rotation. A) t (hours).

velocity components obtained through the single integration of the accelerometer outputs are multiplied by $2\Omega \sin \lambda$ and subsequently fed to the accelerometers as the shift voltages.

The deviation in missile trajectory as a result of the Coriolis acceleration will be at its greatest in the case of high-speed missiles flying in the upper latitudes (near the poles). In this case, the missile will be deflected to the east in the northern hemisphere and to the west, with respect to the calculated point, in the southern hemisphere.

In more complex systems, when the missile flies at various altitudes and its vertical component of velocity changes within a wide range, additional correction factors are introduced, and these are not characteristic of the inertial system.

Despite the fact that the operating principle of the inertial sys-

tem is not complex, for long-range missiles it was impossible to achieve this system earlier because the level of engineering was not yet sufficiently advanced to satisfy the rigid requirements that are imposed on the degree of accuracy required of such basic elements of the system as the gyroscopes and accelerometers. The accuracy of guidance is a strong function of both the quality and accuracy of these two instruments.

It has been demonstrated by calculation that in order to achieve guidance by means of an inertial guidance system for an aircraft flying at a velocity of 1100 km/hr to its destination, some 1000 km from its take-off point, and if this guidance is to be achieved with an accuracy of up to 1 km, the angular velocity of the deflection (drift) of the gyroscope axis must not exceed 0.01 deg/hr. Gyroscopes of conventional design are incapable of achieving such accuracy.

It has been reported in the press that new designs of small-dimension gyroscopes have been developed to operate with a number of degrees of freedom, and the accuracy of these gyroscopes substantially exceeds the accuracy of the earlier models, because of the elimination of the hinged suspension in the designs of these new gyroscopes and the positioning of the gyroscope elements within a fluid. Such gyroscopes are referred to as floating gyroscopes. They are constructed in the following manner (Fig. 107). The rotor of the gyroscope whose axis has been mounted on roller bearings is placed within an air-tight shell which is immersed in a high-viscosity liquid and maintained within the center of an external frame (container) in a state of neutral equilibrium. This eliminates almost entirely the friction observed in the case of hinge-suspension bearings. As a result of this design the gyroscope is rendered incapable of moving and striking against the walls of the container even in the case of the greatest

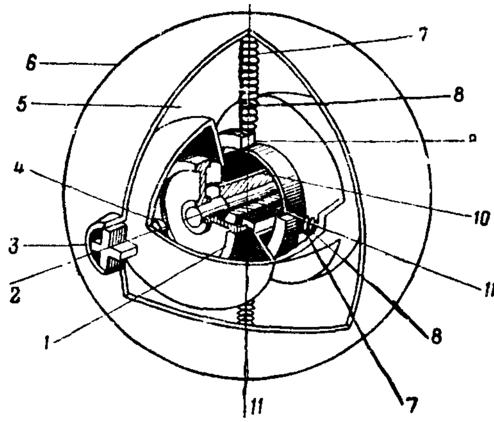

Fig. 107. Construction of a free-floating gyroscope: 1) gyroscope rotor; 2) axis of rotation; 3) position-error indicator; 4) sensing-element magnet; 5) suspension fluid; 6) outer frame; 7) current-supply wiring; 8) wire centering thread; 9) annular frame of universal joint; 10) gyromotor; 11) stabilized axis.

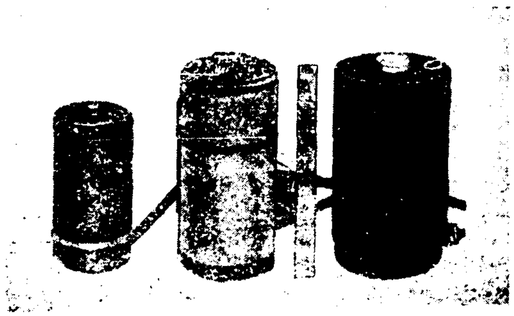

Fig. 108. Outside view of some floating gyroscopes.

shock loads, since the load in this case is distributed uniformly over the entire surface of the gyroscope container. The container is mounted on a platform by means of a universal joint and is stabilized by a servodrive that is operated by the corresponding sensing elements. An external view of such gyroscopes is presented in Fig. 108.

In addition to the development of high-quality gyroscopes, accel-

erometers have been developed and are being manufactured with negligibly small frictional resistance, making possible the measurement of acceleration with greater accuracy than the earlier models. There was a report in the foreign press that an error of even 0.00003 m/sec^2 in the zero setting of the acceleration sensing element will result in a distance-measurement error of the order of 1160 m in the case of a flight lasting 8800 sec at a flight velocity of $M = 3$ for intercontinental missiles with an effective range of 8000 km. At greater velocities the miss distance will be correspondingly smaller. Hence we can see the requirements in accuracy that are called for on the part of the accelerometers.

In the design of the computer installations it is important to bear in mind that the magnitude of missile acceleration may change within a range of 300,000:1 and more, since acceleration in actual fact changes from its maximum value of several tens of g to a fraction of a g. Therefore, the voltage at the integrator will also change within a wide range.

Depending on the composition of the navigational instruments employed in the inertial system and depending on their technical data, systems may vary in complexity and tactical data. Systems exhibiting less guidance accuracy are employed for short-range missiles, while those systems that are more accurate are used for long-range missiles.

Contemporary inertial systems using perfected equipment and instruments exhibit rather high guidance accuracy and can be used for long-range missiles and intercontinental ballistic rockets and airplane-type missiles.

All of the basic elements have now been developed for the inertial system; however, these systems are continuously subjected to improvement.

The inertial guidance system has many advantages over other systems. In the future, this system will be able to satisfy more completely the requirements of an ideal system.

The chief advantages of the inertial system are the following: complete autonomy and independence of the system from external conditions; the possibility of operation at any time and in any weather; absolute resistance to interference; the possibility of launching an unlimited number of missiles simultaneously.

The basic shortcoming of the system is the fact that the system can achieve the guidance of a missile only against such targets as remain fixed with respect to the earth's surface throughout the entire period of missile flight. Another shortcoming that is of significant importance from the standpoint of long-range missile guidance is the increase in the guidance error with increasing range: the error increases approximately proportionately to the flight time.

Still another shortcoming of this system is the complexity of manufacture.

§3. ASTRONAVIGATIONAL GUIDANCE SYSTEM

Astronavigational systems based on the principle of navigating according to celestial light sources make it possible to correct continuously the trajectory of missile flight, and this eliminates the shortcomings that are inherent in the inertial systems, i.e., the increasing guidance errors with increasing distance.

It is well known that the position of a point or a moving object at the surface of the earth can be determined by means of astronomical observations. Such determination of location is based on the following basic statements of astronomical geometry (Fig. 109). The straight line connecting the center of the earth and some celestial light source intersects the terrestrial surface at a point referred to as the geo-

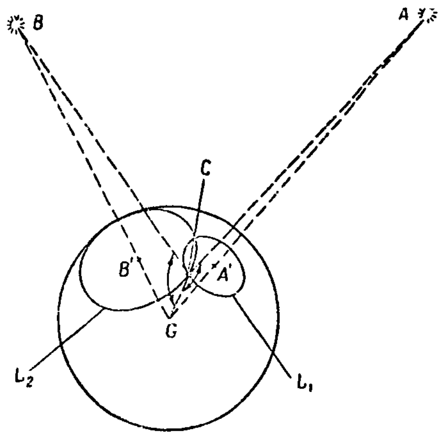

Fig. 109. The principle of determining the position of an object by means of astronomical observation of two sources of light: A) first light source; B) second light source; G) center of earth; C) observation point; L_1) position line of first light source; L_2) position line of second light source; CA) line of sight of first light source; CB) line of sight of second light source; ACG) altitude of first light source with respect to vertical; BCG) altitude of second light source with respect to vertical; A^1 and B^1) geographic positions of light sources.

graphic location of the light source. The light source is at its zenith at this point and its altitude is equal to 90°. As an observer moves away from the geographic location of the light source, the light source will move away from the zenith, and its altitude will diminish. The circle drawn on the earth's surface about the geographic location of the light source (this circle being equal to the distance [in units of arc] that the light source has moved away from the zenith) is the position line of an observer situated on one of the points of this circle. The position line of the observer is the line of equal light-

source altitudes. The position of the geographic location of the light source on the surface of the earth can be calculated by means of an astronomy almanac, and the radius of the circle described by the position line is measured in terms of the light-source altitude.

The altitude of the celestial light sources (stars, the sun, the moon, and the planets), i.e., the actual angle between the line of sight to the light source and the plane of the local horizon, is measured by means of special instruments. It is possible to calculate and plot on a chart the position line of an object at the instant of observation according to the altitude of the light source and the time of observations; this line is referred to as the position line. If the altitudes of two light sources have been measured and if two position lines have been determined, the point of intersection of these lines indicates the location of an object. With the intersection of two position lines we generally obtain two points; however, if we know the approximate position of the object, one point may easily be eliminated. The other point, expressed in astronomical coordinates, determines the true position of the object at a given instant of time with rather high accuracy.

Thus, if the altitude of a light source with respect to the plane of the horizon (or the vertical) is continuously being measured on a missile and if these data are related to time, the position of the missile with respect to the earth will be determined and this information, required for the guidance of the missile to the target, can be obtained. In this case it is necessary for the instruments measuring the altitude of the chosen light sources to be mounted on a gyrostabilized platform and these should always be directed at the light sources, i.e., they should track these light sources automatically. Such instruments measure the angular coordinates of the light sources automatic-

ally and are called sextants (Fig. 110). Light sources emitting various types of radiation are used for the functioning of these instruments in astronavigational systems, i.e., light, radiowaves. If optical instruments (telescopes) are being used for automatic sextants, the system is referred to as an optical astronavigational system. If radiosextants are being used in the system, the system is identified as a radioastronavigational system.

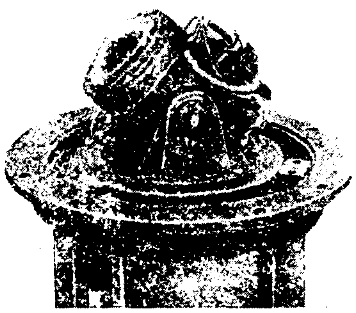

Fig. 110. Photoelectric telescope of an astronavigational sextant.

The sextants in astronavigational systems are actually correction devices which, in the case of the deflection of a missile from its calculated trajectory, transmit the correction signals to the autopilot of the missile. Depending on the complexity of the system, the autopilot, in this case, is either an extremely simple gyroscopic control system or a more complex system of autonomous control, much like an inertial system.

In the latter case, for purposes of missile control, use is made of the same type of gyroscopically stabilized platform as in the inertial system, as well as of accelerometers, integrators, computers, and the remaining instruments which provide for autonomous missile control.

An altimeter is employed to maintain a missile at a given flight altitude and this altimeter, in the case of the deflection of the mis-

sile from the required altitude, makes it possible to derive an error signal and transmit this signal to the autopilot for purposes of correcting the flight altitude.

After a missile has been equipped with the required astronavigational instruments (Fig. 111), the task is to guide the missile from the initial point to the point of target position in accordance with a predetermined heading established by the program installation of the missile. If the exact coordinates of the launching site and those of the target are known, the calculated trajectory of missile flight may be supplied in the form of a predetermined function relating changes in bearing obtained from selected light sources. This function is introduced into the program installation of the missile.

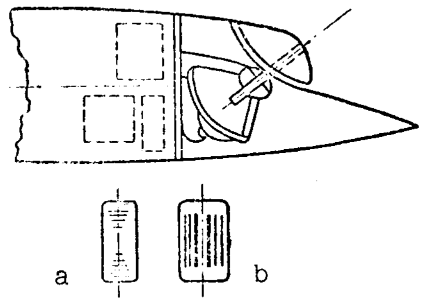

Fig. 111. Schematic representation of disposition of tracking telescope on airplane-type missile: a and b) modulation rasters.

Thus the program of the astronavigational system is a recording, achieved in some manner, of the previously calculated mutual position of the missile and the selected stars, and this position is determined for each instant of missile travel.

During the flight the actual coordinates of the missile are measured at each instant of time by means of an automatic sextant and are given in the form of the actual altitude of the light source at the instant of measurement. If the obtained value of this angle were to be

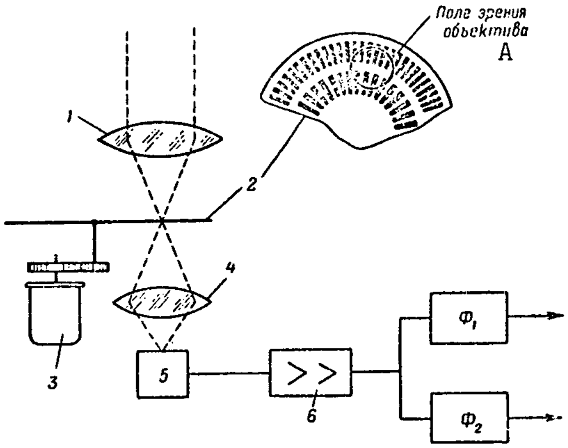

Fig. 112. Simplified diagram of the construction of the tracking telescope: 1) objective; 2) modulation disk with rasters; 3) motor for rotation of disk; 4) condenser; 5) photocell; 6) amplifier; Φ_1) filter adjusted for frequency f_1; Φ_2) filter adjusted for frequency f_2. A) Field of view of objective.

compared against the programmed true value of the altitude of the light source, it might be possible to obtain a signal which characterizes the azimuthal error of the missile which, by means of the autopilot, will force the missile to turn into the proper path.

As a rule, two light sources are usually tracked in the optical astronavigational guidance system, since the observation of two light sources simultaneously eliminates the indefiniteness in the determination of missile location. However, if in addition to the altitude of the light source the azimuth of the light source is also measured (the angle between the meridian at the point of observation and the arc to the surface of the earth, this arc obtained through the intersection by the earth of the plane passing through the center of the earth, the point of observation, and the geographic location of the light source), it might be possible to achieve an astronavigational guidance system

that tracks a single light source, since the azimuth makes it possible to determine the specific point of the location of an observer or an object on the position line (the circle).

The guidance accuracy of the astronavigational system is primarily determined by the accuracy with which the coordinates of the light source are measured by the automatic tracking telescopes.

Let us examine the construction and operating principle of the tracking optical systems used in astronavigational systems.

The sextants with optical tracking telescopes used in astronavigational systems (Fig. 112) are quite similar in construction to the optical heat-orientation devices of the infrared homing systems which use optical lenses. Typical designs of these and similar optical systems involve the use of an objective (consisting of one or more lenses), modulation disks with applied rasters, which are rotated by means of special electric motors, and a condenser which focuses the light flux. The modulation-disk modulated light flux impinges on the photocell which serves as the sensing element of this system. A pulsed photocurrent is obtained at the output of the photocell, and the frequency of this current will be a function of the portion of the modulation disk on which the image of the light source impinges. These pulses, after amplification, are transmitted to the corresponding filters and then control the motors which turn the telescope so that the image of the light source shifts onto the line between the rasters, and this will happen when the light source is exactly on the optical axis of the telescope. Thus, the sextant automatically tracks the selected light source. The tracking of the light source is carried out along two channels: altitude and azimuth.

In order to capture the chosen light source in the telescope the sextant initially must operate in a search regime of definite azimuthal

and altitude limits.

According to foreign-press reports the American company "Kollsmen Instrument" recently developed and is now manufacturing an automatic photoelectric sextant intended for aircraft guidance, but is suitable for utilization in the guidance systems of long-range missiles. The construction and operation of such a sextant are of particular interest.

The sextant consists of a light-sensitive telescope, an amplifier, and an indicator unit. The telescope is connected to a system of servomechanisms and is capable of shifting from 0° to 90° in elevation and 360° with respect to the azimuth, thus making it possible automatically and continuously to measure the altitude of the celestial light source in order to determine the position line and the azimuth of the light source, this data necessary for the determination of the heading of an aircraft or a missile. The telescope is set manually in the approximate direction (for an aircraft) or by means of a memory device (for a missile), and the scanning mechanism carries out the search for the light source by means of rocking the telescope to the left and to the right, gradually changing the elevation; thus it is possible to scan 7° of space with respect to the azimuth and 5° with respect to elevation. After the setting of the telescope for the chosen light source, the light source is "captured" and the instrument switches to a regime of automatic tracking.

A telescope exhibits the following features. If the sextant is perfectly horizontal and directed toward the light source at an elevation of 12°, the objective of the telescope is fully used; if, however, the light source is situated on the horizon only 89% of the objective area is utilized. The statistical error in the azimuth- and elevation-angle tracking regime does not exceed 0.5 minutes of arc, whereas the corresponding dynamic error, for angular velocities of shift not in

excess of 10 deg/sec, does not exceed 2 minutes of arc. The beams of light emitted by a star, a planet, or the sun, are gathered by a lens having a diameter of about 58 mm and then modulated twice by means of a rotating obturator in the shape of a semicircle and by means of a rotating disk with rasters, said disk situated in the immediate vicinity of the image plane. In this case, the width of the opaque raster sectors is such that the entire image of the star and a substantial portion of the image of the sun are modulated. There will be no modulation in the case of such luminous sources as the Northern Lights, clouds illuminated by the moon, etc., entering the field of view of the objective, and this is extremely important from the standpoint of recognizing a star and tracking it. A modulated beam of light from a star impinges on a light-sensitive screen. The shifting of the light spot from a star over the light-sensitive screen produces a signal which is fed into a computer device that works out the control signals to maintain the missile on its given heading.

The sensitivity of the instrument is adequate to track stars of the first and second magnitudes.* In tracking the sun (during the day) a filter is placed in front of the objective, and this filter is moved aside in tracking planets or stars (at night). Stars or planets can be recognized according to the amplitude of the received signal.

The sextant is equipped with a device to average the continuously incoming sextant-measured data on star altitude prior to the transmission of these data to the computer. The basic purpose of the computer is to solve the spherical-triangle problem. This problem is an apparent mechanical analog to the stellar sphere in which the necessary measurements are carried out without any additional trigonometric calculations and the plotting of the measurement data onto a chart. The latitude and longitude of observation, the angle of declination, and

Greenwich time are used as the input data for the computer. Data pertaining to the azimuth and altitude of the light source are taken from the computer output.

One of the most important problems for an astronavigational system, just as in the case of an inertial system, is the maintenance (in flight) of a strictly horizontal plane or, what is the same, an indication of the direction of the true vertical. For straight-line flight at a given altitude this problem can be resolved rather satisfactorily. However, in the case of complex maneuvering, particularly after an extended turn, there may appear or accumulate a certain error in some of the vertical sensors such as the vertical or horizontal gyroscopes. In such cases it becomes necessary to achieve the reliable stabilization of the platform on which the optical star-tracking systems are mounted.

The complexity of an astronavigational system will be a function of the rated effective range of the missile. In the case of long-range missiles there will be a more complex system, since it must provide for high guidance accuracy over great distances, and for this purpose the system must be provided with a reliably stabilized platform and the system must be in a position to take into consideration correction factors for wind, rotation of the earth, etc. In the case of distances in excess of 4800 km or in the case of a flight lasting longer than three hours, the tracking procedure is switched from one star to another. Such a system may function as an inertial system at such times as when the stars are not visible to the tracking telescopes.

Astronavigational systems may be used for missiles of the "ground-to-ground" and "air-to-ground" classes of extremely great effective range. According to available data, certain of the intercontinental missiles developed in the USA will be equipped with astronavigational

guidance systems. The effective range of such missiles will be approximately 8000 km. Guidance accuracy will depend on the optical instruments that are employed and according to some sources amounts to 13 km, whereas other sources report a guidance accuracy of 3.2 km.

According to many reports, an intercontinental missile such as the "Snark" must have been equipped with an astronavigational guidance system.

The "Snark" missile must have been launched with solid-propellant booster engines. Upon attaining a cruising altitude, at which time a velocity corresponding to $M = 0.9$ should have been attained, the guidance system which represents a combination of an astronavigational and an inertial control system is actuated. The autopilot which established the initial heading and trajectory on the basis of signals received from the programming device during the climb should be switched off during flight along the given heading and be actuated only when the telescope is deflected from the selected star (for example, as a result of the turbulence of atmospheric layers or if the star is covered by clouds) and additional heading correction is required.

The astronavigational guidance system exhibits the following basic tactical advantages: rather great range; comparatively high guidance accuracy that is little dependent on range or missile flight time; it is virtually not subject to interference on the part of the enemy (it is possible that attempts may be made to create so-called "false stars" and to use "optical shrouds"; however, it is an extremely difficult task to create such interference); finally, the astronavigational system makes it possible to launch an unlimited number of missiles simultaneously.

The shortcomings of the astronavigational system are the following:

restrictions as to altitude; the system may be employed reliably only at altitudes above the maximum altitude of the cloud cover. At lower altitudes it cannot be used at any time of the day or under any weather conditions. In the case of guidance by the stars, the most suitable conditions are the following: night, and a cloudless sky. Additional special devices are needed to track stars during the day;

limitations as to maneuverability; it is difficult to track a star in the case of unlimited angles of roll and pitch, as well as at low altitudes;

the possibility of natural interference; the Northern Lights, atmospheric turbulence, the cloud cover (at low altitudes).

All of the above-enumerated restrictions can be eliminated if a combined system consisting of elements of the astronavigational and inertial systems are used for intercontinental missiles.

Another shortcoming of the astronavigational system is the fact that the missile can be used only against such targets as remain fixed during the period of missile flight. Only the utilization of a homing system during the final phase of the flight, if it can provide for target recognition, can occasionally eliminate this shortcoming.

§4. RADIOASTRONAVIGATIONAL GUIDANCE SYSTEMS

Thanks to the latest achievements of the comparatively new but rapidly developing science of radioastronomy it has now become possible to produce yet another autonomous guidance system for long-range missiles, i.e., the radioastronavigational system.

It has been established that the sun as well as other celestial bodies, exhibiting high temperature, emit electromagnetic energy in the form of chaotically fluctuating noises that differ little in character from the input noises of a receiver. To isolate a useful radiosignal from an interplanetary source on a background of receiver

noises a definite "coloration" is imparted to the useful signal, for which purpose most frequently the signal is modulated with a known low frequency.

This principle serves as the basis for the design of the new navigational instrument referred to as a radiosextant which makes it possible, with great accuracy, to obtain bearings by means of a celestial radio emitter and to determine the position of the object on which the radiosextant is trained.

The sun is the most powerful and therefore the most suitable source emitting electromagnetic waves; therefore, the recently developed radiosextant is designed to obtain a radiobearing on the sun. The basic advantage of such a radiosextant, in comparison with the conventional navigator's sextant, lies in the fact that it is possible to find the direction to the sun by means of this sextant regardless of the weather conditions. Moreover, the radiosextant automatically tracks the sun and as a result can continuously yield measurement results. The radiosextant must be mounted on a spatially stabilized platform which, in combination with the vertical indicator (for example, the horizontal gyroscope), forms a coordinate plane relative to which the altitudes of the light sources can be measured.

Externally the radiosextant resembles a small radar station with an automatic target-tracking unit. The antenna of the radiosextant is directed toward the sun, and the antenna beam scans the solar limb. Regardless of the deviation of the antenna axis from the line to the center of the sun, the received signals will be modulated by some frequency determined by the speed of antenna rotation. The isolation of the received signal and its comparison with the reference signals will make it possible to determine the azimuth and elevation, with respect to the sun, of the object on which the sextant is trained. These

data will be fed into the computer into which are also fed the data from other instruments necessary for the determination of missile position (heading, distance covered). The computer will work out quickly and with great accuracy the coordinates of missile position.

The first radiosextants installed aboard aircraft and seagoing vessels were designed to function on a 1.9 cm wave. One such aircraft radiosextant (Fig. 113), with an over-all weight of 45 kg, consists of several compact units with an antenna which has a reflector that is 60 cm in diameter. The receiver block of this sextant is mounted directly behind the antenna reflector.

Extensive operation and a study of the features involved in the reception of radio emissions from the sun under various conditions on a 1.9 cm wave have shown that this wavelength provides for extremely

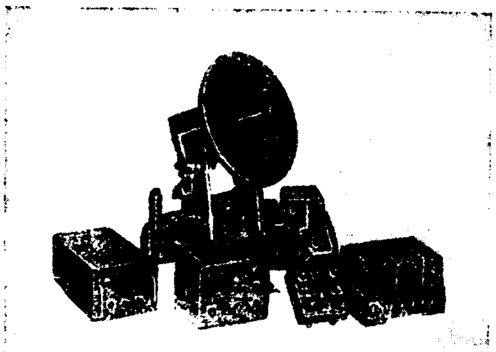

Fig. 113. External view of radiosextant.

reliable radiosextant operation in any weather. Snowfall, fog, rain, thunderstorms, or heavy overcast have an insignificant effect on the accuracy of instrument readings. Only in the case in which it was necessary to observe the sun situated low above the horizon did we note a slight attenuation in the level of the received signals, and this resulted in a drop in tracking accuracy. As is shown by an analysis of the results obtained from the measurement of the sun's altitude,

the probable sextant error with respect to altitude amounts to 0.032°, i.e., less than 2 minutes of arc.

The 1.9 cm wavelength for which the first radiosextants were designed was selected as a compromise, to account for the magnitude of atmospheric absorption and the achievement of suitable dimensions for the radio equipment to be used aboard the aircraft.

The utilization of shorter waves increases the accuracy with which the altitude of the sun can be measured. An 8.7 mm wave was selected in the most recent experiments, and this wavelength corresponds to a point of minimum atmospheric absorption between the two absorption maxima for oxygen and water vapors on the 6 mm and 1.25 cm waves. To verify operating conditions on the 8.7 mm wave, an experimental model of a surface-vessel radiosextant was designed with an antenna reflector having a diameter of 112 cm an a directivity pattern on this wave approximately 0.5° wide, which is in exact correspondence with the angular diameter of the sun. In this case, the probable radiosextant error amounted to about 0.017°, i.e., of the order of one minute of arc.

The operation of the radiosextant on the 8.7 mm wave, under various meteorological conditions, demonstrated that in this case the sextant is more subject to the effects of atmospheric conditions than the radiosextant that operates on longer waves. Despite the extremely perceptible influence of the meteorological conditions on the characteristics of a sextant operating on the 8.7 mm wave, this radiosextant exhibited adequate reliability of operation regardless of the weather. While the 8.7 mm wave is suitable for radiosextants employed aboard seagoing vessels, in the case of the radiosextants mounted in aircraft or guided missiles, the effect of atmospheric phenomena need not be taken too seriously, since even at a low flight altitude the dominant

mass of the atmospheric moisture remains below the flight altitude and no longer exerts any influence on the functioning of the radiosextant. The utilization of this wavelength, however, will make it possible to reduce the antenna diameter of the aircraft radiosextant to 38 cm.

The possibilities of utilizing the moon and stars as celestial points of orientation for radiosextants is being studied at the present time. The moon is regarded as a weak source of electromagnetic radiation; however, as has been demonstrated experimentally, with the utilization of a radiosextant operating on the 8.7 mm wave, it is possible to determine the angular coordinates of the moon.

This serves to expand the potentials of the radioastronavigational system, since it makes it possible to design a radiosextant that is suitable for utilization at night as well. With respect to the utilization of the electromagnetic radiation of stars, as has been shown by investigations, this emission in the frequency range being considered is extremely weak. The maximum of these emissions falls within the 10 cm range and higher. In this case, the antennas of the radiosextants will be somewhat too cumbersome and unsuitable for installation aboard aircraft and missiles. It is felt, however, that the intensity of radioemissions from stars is adequate for purposes of utilizing radiosextants in marine navigation; therefore, through the subsequent improvement of the techniques of radioastronomy, it will become possible to design radiosextants for purposes of aircraft and missile guidance by the stars.

Thus, the radiosextant is the chief radically new element of the radioastronavigational guidance system. In all other respects, this system is very similar to the astronavigational system.

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242 The North star is regarded as a star of the second magnitude.

Chapter 9

COMBINED GUIDANCE SYSTEMS

A definite control system is selected for each specific missile during its design stage. The selection of the control system and of its most important element, i.e., the guidance system, is carried out in consideration of a great many factors.

First of all, the selection of a control system for any class of missile is based on the rated effective range of the missile, the required accuracy of guidance to the target, reliability, the most suitable missile flight-trajectory from the standpoint of standard tactics (the guidance method), the characteristics of the targets, the space taken up by and the number of on-board pieces of equipment, and the equipment at the control point (especially aboard a surface vessel, aircraft), and the ability of the system to ward off interference.

In addition to the basic characteristics the following properties and features of the control systems, the missile, and the surrounding area are taken into consideration: the presence of a booster engine and its effect on the operation of the control system; the rigidity of the missile and the tolerable G-forces; the scattering of the missiles after launch; natural and meteorological conditions in the region of possible missile flight; and the possibility of natural interference; the necessity of launching several missiles simultaneously, etc.

After an examination of all of the characteristic systems whose utilization is most probable for a specific missile, and after an

analysis of the advantages and shortcomings of these systems, a definite control system is selected; this system will satisfy the imposed requirements to the maximum. It happens frequently that the selected system satisfies in adequate measure all of the basic requirements and it is thus accepted and incorporated into the design. But there are cases in which none of the systems satisfies certain of the basic requirements and the question then arises as to whether or not to employ a combined control system consisting of two or sometimes three various systems which, in conjunction with each other, would be capable of satisfying all of the basic requirements that have been imposed. In such cases, the on-board missile control system is most frequently regarded as a single whole and it is only that various guidance systems are employed, these being switched on at the appropriate instant of time so that instead of one, another begins to function.

In actual practice we may encounter cases in which, in the case of multistage missiles employing tandem boosters, it becomes necessary to install completely independent control systems for the individual stages, i.e., a special guidance system, an on-board control system, and control units must be provided for each stage. But this is somewhat too complex and such a combination of control systems may be resorted to in extraordinary cases only.

The combination of control systems (in the majority of cases, only guidance systems) is generally carried out when none of the systems under consideration is capable of satisfying the basic tactical requirements, and this primarily in the following cases:

1) if the missile range is greater than the effective range of the most suitable guidance system;

2) if the guidance accuracy of the most suitable system is inadequate in comparison to the given accuracy during the final phase;

3) if great scattering of the missiles takes place after launching, during the initial flight phase, threatening to carry the missile beyond the operating sphere of the selected guidance system before the latter comes into operation;

4) if from a tactical standpoint the flight trajectory of the missile must exhibit a configuration along individual segments such as cannot be provided by either the selected or the most suitable system;

5) if the most suitable guidance system is a system that is capable of guiding the missile only against fixed targets, whereas the target is a moving target (generally slowly moving), etc.

Depending on the class of missiles and the guidance systems employed, the entire course of flight for each missile, from the instant of launch to impact against the target, can be divided into several phases differing from one another in a variety of characteristics: flight velocity, missile weight, controllability, curvature of trajectory, guidance method, etc. In the general case, the entire flight of a missile can be divided into three phases: the initial phase, the middle phase, and the final phase. In certain cases, some one of these phases may be skipped. It is frequently the case that various guidance systems are employed during various phases of missile flight, i.e., in general, combined guidance systems are used.

If a combined system is used for purposes of guiding a missile, the entire guidance process is divided into several phases, two or three depending on the number of guidance systems used. These guidance phases most frequently coincide with the corresponding missile-flight phases and have accordingly been designated as initial guidance, guidance over the middle segment of the trajectory (the segment during which the missile approaches the target), and final guidance.

The initial-guidance phase is one of short duration and encom-

passes the first portion of the missile-flight trajectory from the instant of launch to the instant of time at which the missile attains the velocity at which it can be guided normally by means of the aerodynamic control surfaces. In the case of multistage missiles, this phase generally lasts to the instant of booster separation. Some missiles are controlled during this phase by means of rotating the combustion chamber of the engine. In the effort to simplify the guidance system, attempts are made to launch the missile so that the control of the missile is taken over by the guidance system at the end of the first phase of the flight, and this system will control the missile along the middle segment of the trajectory, thus eliminating the necessity of a special guidance system for the initial phase of missile flight. However, in a number of cases, and particularly in the case of significant missile scattering during launch, a special guidance system may be employed for the initial phase alone, although this serves to complicate the entire guidance system (for example, beam-gathering and gyroscopic systems, i.e., simple inertial systems, etc.).

The guidance phase along the middle segment of the trajectory of missile flight is the basic and longest-lasting phase, frequently determining the effective range of a guided missile. The guidance system employed along this segment of the trajectory is the basic guidance system for a given missile. The solution to the problem of whether or not it is necessary to use more exacting guidance during the final phase of missile flight, i.e., during the approach of the missile to the target, depends on the guidance accuracy of this system.

The final guidance phase encompasses the last segment of the missile-flight trajectory and is also generally of short duration. If the guided missile exhibits a short effective range and its basic guidance system is highly accurate, no special system for final guid-

ance is employed during the final phase. However, if the accuracy of the guidance system along the middle segment of the trajectory is not too high, and this is particularly important for long-range missiles, special final-guidance systems are used; the effective range of these special final-guidance systems is not overly great, but their guidance accuracy is rather high.

Thus, the selection of guidance systems for various missiles as the only system or as a component part of a combined system is based on the tactical considerations of the combat purposes for which the missile is to be employed, as well as on the technical potentials of each guidance system (primarily, the effective range and the guidance accuracy), and the engineering characteristics of the launching installations.

The launching installations, in terms of missile mounting, are divided into installations with a constant angle of elevation and installations with variable angles of elevation. For long-range missiles, particularly for ballistic missiles, launching sites with a constant angle of elevation (generally amounting to 90° to the horizon) are used. For shorter-range missiles, exhibiting comparatively low flight velocity, a constant angle of elevation is also used, but it is not great in magnitude (7-12°). In the case of short-range missiles exhibiting low flight velocity and launched against moving targets, launching sites with a variable angle of elevation are used; this angle of elevation is sometimes calculated by means of the computer in the fire-control system and the calculation is carried out on the basis of the data on target position; the angle of elevation is set automatically.

The complexity in the design of the launching site, which is a function of the accuracy of missile launching, is determined by the

position of its installation. In the case of ground launching sites there are unlimited possibilities for the establishment of strong and convenient designs. Launching sites aboard surface vessels must be kept to a minimum in weight and dimension and the rolling of the vessel must be taken into consideration. This makes launching sites aboard surface vessels more complex. The most complex and inconvenient launching sites are those aboard aircraft. In the case of carrier aircraft the missiles are generally suspended beneath the wings (2-4 pieces) and the missiles are dropped from the suspension device at the required instant of time with an initial velocity that is equal to the velocity of the aircraft.

The launching installations for submarines are even more complex, since these launch guided missiles from beneath the water. These launching installations are generally positioned in the middle portion of the submarine. The missiles are housed in a special magazine hold (container). Some of the special submarine-missile carriers developed in the USA have been designed to take up to 10 guided missiles on board. After each launch a special device must shift the remaining missiles in order to compensate for a shifting center of gravity.

Thus, the necessity of utilizing a special system for the initial guidance phase depends on the properties and capabilities of the launching sites to launch the missiles in such a manner as to insure their reliable entry into the effective sphere of the system which is in operation during the approach phase.

The required missile-guidance accuracy is determined by the dimensions of the target, the type of fuse, the effectiveness of the warhead, and the vulnerability of the target. Guidance accuracy may be set either for a direct hit, or for a permissible miss distance.

In various of the guidance systems the relationship between the

guidance accuracy for the missiles and the range $\underline{\underline{D}}$ varies. In the case of homing and television systems the guidance errors theoretically diminish as the missile approaches the target, i.e., with increasing distance from the launching site (if we do not take into consideration the transient responses in the control system). However, the accuracy of the homing systems is a strong function of the guidance method, the velocity, and the maneuvering of the target and, in actual practice, is frequently impaired as the missile approaches the target.

In the case of beam-rider guidance systems, as well as in the case of command, inertial, and certain of the other guidance systems, guidance errors increase approximately in proportion to range. If the missiles (usually, ballistic missiles) are guided only during the initial flight phase, the errors increase in accordance with the following function $\underline{\underline{D}}^n$, where $n > 1$.

Since the magnitude of the miss distance for a given system exhibits a certain amount of scatter, the primary criterion for evaluating the efficiency of a system is the probability of target damage, which is generally determined experimentally, i.e., by actual firing.

The combination of systems is employed for all possible types of missiles. Let us examine the possible versions of combined guidance systems for missiles of various classes.

<u>For missiles of the "air-to-air" class</u>. Missiles of this class are short-range missiles and it is generally sufficient to employ a single system for purposes of guiding such missiles. We can use the following guidance systems here: passive, active, semiactive, beam-rider, and command.

At the instant of launch the missile has a velocity that is equal to the velocity of the carrier aircraft and in order to eliminate errors during launch that are greater than those permitted by the

guidance system it is necessary to have a missile that is sufficiently stable from the aerodynamic standpoint and one that will not veer to the side until the guidance systems begins to function reliably.

In command systems the missile must not be permitted to escape the field of view of the control system during the launch phase. In the case of the beam-rider guidance system the proper launch angle must be calculated to insure the missile being guided in by the beam. During utilization of the last system a final guidance system may be employed in special cases and for this a semiactive homing system may be used. However, in actual practice the guidance systems for missiles of this class are generally not combined.

For missiles of the "air-to-ground" class. The possible combination of guidance systems for missiles of this class depends primarily on the effective design range of the missile.

Initial guidance, as in the case of missiles of the "air-to-air" class, is of extremely short duration and may be provided by increased aerodynamic missile stability during launch.

For purposes of guiding short-range missiles we employ the following systems: homing, beam-rider, and command. However, homing systems and the beam-rider methods cannot be employed against all targets, but only against those that present a contrast against the surrounding background. For targets that do not exhibit radar contrast, the beam-rider guidance system can be employed if the antenna of the radar unit is coupled with an optical sighting device in such a manner that the sighting line of the aiming device coincides, or virtually coincides, with the axis of the beam. Of the command systems the most feasible is the visual or radar single-beam system which involves the installation of a responder aboard the missile. In such cases, generally, no individual final-guidance system is employed.

Combined guidance systems are used in order to guide a missile to a target that is very far away. The beam-rider or command systems are used as the basic guidance systems for the middle segment of the trajectory. However, a reduction in guidance accuracy with increasing distance is characteristic of both of these systems. Therefore, final guidance in the case of great distances often becomes unnecessary. Active homing systems are used for final guidance, if the target exhibits radar contrast; passive homing is used if the target emits thermal energy of a high enough level.

For missiles of the "ground-to-air" class. In order to knock an enemy aircraft out of the sky at the greatest possible distance from the side being defended, i.e., at a distance greater than the effective range of the weapons aboard the enemy aircraft, it is necessary to use guidance systems that exhibit the corresponding range. In such cases we can use semiactive homing systems, as well as various versions of the beam-rider or command systems. When we use beam-rider or radar command systems in order to achieve greater guidance accuracy, final guidance by means of active or passive homing systems may be employed.

The need for initial guidance is determined by the capability of the missile to be gathered in by the radar beam.

Special beam-gathering systems as well as simple gyroscopic systems and programming may be employed for initial guidance.

If the rated range of the missile is not too great, active or passive homing systems may be employed for purposes of guidance.

For missiles of the "ground-to-ground" class. Missiles of this class are divided into airplane-type and ballistic missiles, capable of flying various distances. The airplane-type short-range missiles can use any one of the autonomous control systems. Another system, specially designed for guidance during the initial phase of the flight,

may be employed. For this purpose we can use either beam-rider or command guidance systems.

In order to guide an airplane-type missile over the approach phase we can use radionavigational, magnetometric, inertial, or astro-navigational systems. The radionavigational and magnetometric systems exhibit a number of significant shortcomings; therefore, the best systems are the inertial and astronavigational systems.

The greater the range of the missile, the greater the need for combined systems. Systems can be combined for the target-approach phase as well. As an example of the latter we can cite the combination of the inertial and astronavigational systems, and this is regarded as the best possible version.

The need for final guidance is determined by the guidance accuracy at the end of the approach phase, the dimensions of the target, and the effective radius of the missile's warhead. Depending on the nature of the target, the final guidance may be achieved by active or passive homing systems, or by means of an inertial system that can provide for a programmed maneuver in order to escape an enemy's countermeasures in order subsequently to dive to the target at the most advantageous angle.

Ballistic missiles exhibiting various effective ranges, including intercontinental missiles, are controlled in the majority of cases only during the initial phase of their flight. Special beam-rider, command, or inertial guidance systems with additional control facilities are employed for this purpose (we have reference here to radar units that operate on the Doppler principle).

Chapter 10

CONTROL SYSTEMS OF CERTAIN GUIDED MISSILES. STRUCTURE AND ORGANIZATION OF FIRING COMPLEXES

§1. THE TWOSTAGE ANTIAIRCRAFT "NIKE" MISSILE FOR GROUND UNITS

The Antiaircraft Defense Forces of the USA place particularly great importance on guided antiaircraft missiles. These missiles are assigned the role of the final barrier which is to destroy all of the aircraft that have managed to penetrate to the area surrounding the most important of the defended positions.

The "Nike" missile is the first antiaircraft guided missile accepted as operational in the USA. Several hundred batteries covering strategically important cities and military installations have been equipped with these missiles. The missile itself is only one of the elements of the antiaircraft "Nike" complex which, in addition to the missiles, includes the launching sites, the guidance stations, the radar scanning network, storage areas, and other equipment.

The "Nike" project came into being in 1944. The missile, in conjunction with its guidance system, was first tested in 1951. In 1952 it was put into mass production; by 1954, this missile complex became part of the weaponry of the antiaircraft units of the United States Army.

The missile has a cruciform arrangement of triangular-shaped main supporting surfaces in line with cruciform control surfaces set on the airframe in a canard configuration. The ailerons are situated at the trailing edges of the wings. The control surfaces are set in the nose of the missile and have the same shape as the wings [i.e.,

cruciform]. Behind the control surfaces there are small protruding triangular-shaped surfaces that contain the antennas of the on-board receiving equipment.

The booster of the missile is equipped with three stabilization surfaces of trapezoidal shape which can be removed during transportation.

An inseparable part of the "Nike" missile from the instant that it is attached to the booster to the instant of launch is a box-shaped guide beam which is set up on the launching installation together with the missile. The launching installation consists of a girder (ramp) with a lateral boom by means of which the missile is raised and set in the initial launching position. The boom is raised by means of a hydraulic drive mechanism.

The missile is launched from a near-vertical position, or more exactly, at an angle of 85° to the horizon. Provision has been made for slight deviation from the vertical in order for the booster to fall at some distance from the launching site after separation so as to ensure the safety of the servicing personnel and the equipment at the launching platform.

The guidance system. The "Nike" missile is guided to a target by means of a two-beam radar command guidance system.* The equipment complex of the guidance system (Fig. 114) includes:

a) two ground automatic missile-target track units, of which one tracks the target, while the other tracks the missile;

b) a ground computer which, on the basis of information on the missile and the target (supplied by the two radar units), calculates the data for the interception of the target and works out these data in the form of commands that are transmitted to the missile over the radar beam;

c) on-board receiving units with antennas for reception of commands to guide missile flight;

d) servomechanisms to deflect control surfaces and other elements of the missile control system.*

In addition, one or several acquisition radar units (circular or sector) are incorporated into the ground equipment complex of the "Nike" system to provide for timely detection of a target and the issuance of instructions to the target-track radar unit.

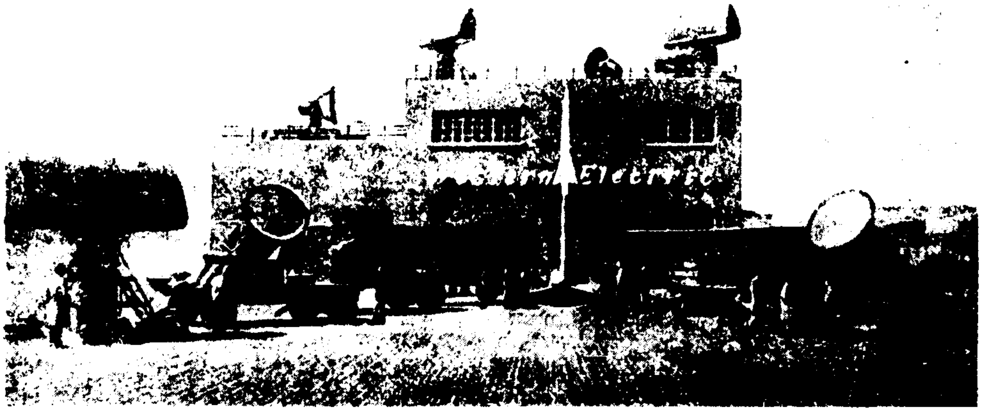

Fig. 114. Ground equipment complex for the guidance system of the "Nike" missile during preliminary tests.

The process of guiding a missile to the target can be reduced to the following. The long-range acquisition radar unit, having detected the target, issues instructions to the target-track radar unit which, upon approach of the target to 50-60 km, "captures" the target and automatically tracks it, determining the instantaneous coordinates of the target and feeding these into the computer. The computer immediately works out the data on the altitude, velocity, and heading of the target. Upon the approach of the target to a certain distance from the

site being defended (as the target enters the zone of missile effectiveness), a missile is launched and this missile, at first, flies almost vertically upward. At this instant the missile enters the beam of the guidance radar unit which immediately begins automatically to track the missile and feeds its instantaneous coordinates to the computer. The computer, on the basis of the incoming information on the instantaneous position of the missile and that of the target, calculates the point at which the missile will come into contact with the target and in accordance with this works out the special commands that will force the missile to fly to the predicted point of contact in order to intercept the target.

The commands that have been encoded by the computer are fed into the modulator of the guidance radar unit and correspondingly modulate the emission of the latter. The receiving unit aboard the missile that is continuously within the beam of the guidance radar unit receives the uniquely modulated radar signals, decodes them, amplifies them, and directs them into the appropriate channels which control the drive mechanisms of specific control surfaces.

A special command signal is transmitted in order to explode the warhead of the missile at the instant of time at which the missile comes into the vicinity of the target, and the calculation here is such that the target enters the zone of scattering missile fragments.

The probability or effectiveness of target destruction by means of a "Nike" missile comes to 65%.* These data have been obtained through firing tests conducted with this missile against radio-controlled pilotless aircraft (propeller-driven QB-17 bombers), flying at an altitude below 9000 m, at a speed of 320 km/hr. In firing against contemporary jet bombers, the effectiveness of the "Nike" missile is regarded as inadequate, since in this case up to 10 "Nike" missiles

are needed, according to certain sources, in order to destroy a single bomber. In recent times measures have been implemented to improve the missile and its guidance system, and as a result there is hope to achieve an effectiveness which will reduce the number of "Nike" missiles required to destroy a single jet bomber to three.

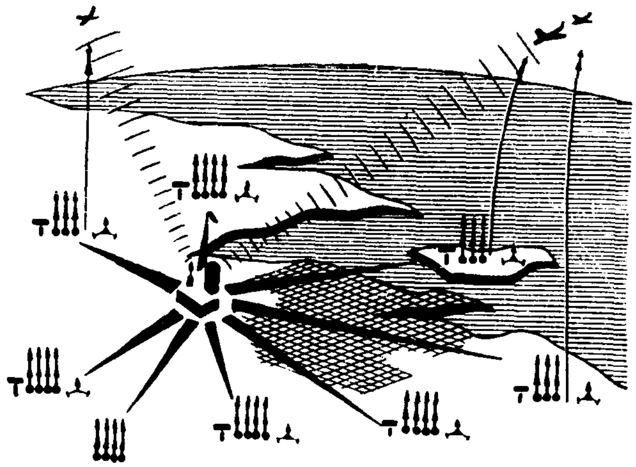

Fig. 115. Diagram of the "Missile Master" system which directed the fire of eight "Nike" antiaircraft missile batteries.

Typical structure of "Nike" missile battery. Several batteries are arranged about each defensive position, and these batteries are responsible for the antiaircraft defense of a zone some 40 km in diameter and up to 18 km in altitude.

Each "Nike" battery consists of a launching installation and a control position. The launching site and the control point are separated from one another, but must, of necessity, preserve visual contact with one another. The launching installation, in turn, consists of two firing platforms and an underground launch-control center, storage facilities (for missiles, fuel, and auxiliary equipment), as well as facilities for the assembly and testing of missiles, and an underground facility to house the personnel.

The firing platforms are situated some 300 to 500 m from one another. There are four launch-ready missiles at each launching installation. The guide beams carrying the missiles move down to meet the boom as the missiles that are combat-ready are fired. The missile can also be fired directly from the lift platform which, having raised the missile upward, simultaneously can bring it into the initial position required for launch. Each battery can have two, four, or six launching installations.

The control point is situated anywhere between 1 and 6 km from the launching installation, depending on the nature of the surrounding terrain. The control point is generally equipped with two radar guidance complexes (in accordance with the number of battery firing platforms). The guidance equipment complex, as has already been pointed out, consists of three radar units: a target acquisition radar unit, a target-track radar unit, and the radar unit that is employed to guide the missile to the target.

Individual "Nike" batteries are joined into battalions, and a single battalion consists of four batteries.

In 1954 the Department of Defense of the USA undertook a program of setting up "Nike" antiaircraft batteries around many of the strategically important cities and military objectives. From one to four (and sometimes five) missile battalions are needed for the defense of each such objective.

The combat activities of the "Nike" missile batteries defending individual areas will be coordinated by means of a special fire-direction system referred to as the "Missile Master," connected to the semiautomatic Antiaircraft Defense System of the USA, i.e., SAGE [Semi-Automatic Ground Environment].

<u>The fire-direction system "Missile Master" (Fig. 115)</u>. The elec-

tronic "Missile Master" system, developed by the Martin Company in conjunction with a number of other companies, was initially intended for the control and coordination of the activities of the "Nike" missile batteries, but it may eventually be refined to direct and coordinate the fire of any anti-aircraft guided missiles.

The basic elements of the "Missile Master" system include the network of target acquisition radar units, the network of automatic data-transmission units, the automatic data-processing equipment, and the indicator devices. This system collects data on the positions of all aircraft within a radius of 320 km, distinguishes the aircraft, makes assignments to individual batteries, and transmits processed data to the indicator screens of the appropriate batteries, thus providing the commander of a battery with all required information. The battery commander selects an appropriate target and launches a guided missile by depressing a button.

The "Missile Master" system must, in this case, perform the following functions:

1) prevent two or more batteries from firing against a single target;

2) in tracking a single target, it must prevent the escape [passage] of another target;

3) prevent destruction of own aircraft during combat.

The system is serviced by three categories of operators; tactical-control operators, target-track radar operators, and recognition operators.

The tactical-control operators observe the combat situation and control the target selection of individual batteries, ensure fast action on the part of combat facilities, and prevent the duplication of fire against a single target. They supervise the activities of the

battery commander and if the latter should err in target selection, they step in and direct the fire of the battery against more important targets.

The target-track radar-unit operators maintain observation of all target signals and their coded characteristics on the indicator screens of the target tracking system and collate their positions with the signal positions derived from other aerial-observation systems such as, for example, from the "SAGE" system. The characteristics of bypassed targets are fed into the tracking system.

The recognition operators are responsible for keeping track of the position of known friendly aircraft in the given area and they must compare the coordinates of these friendly aircraft with the data of the targets that are being processed by the system. At any instant of time these operators can stop any battery commander if the battery is firing on a friendly aircraft.

Shortcomings of the "Nike" system. In addition to the inadequate effectiveness of the "Nike" missiles when used against high-speed and high-altitude targets, there are the following more significant shortcomings of the "Nike" system:

1. When we take into consideration the high velocities of contemporary bombers and the possibilities of using guided bombs and thermonuclear weapons, the radius of missile effectiveness is small.

2. The superiority in terms of flight velocity on the part of the "Nike" missiles, in comparison to contemporary aircraft, is not overly great. This restricts in great measure the "field-of-fire" for the "Nike" units against enemy aircraft.

3. The guidance system of the missile is complex and requires a large quantity of ground equipment. As a result, the reliability of the guidance system's equipment is inadequate.

4. The radar guidance system used for "Nike" missiles exhibits limited capacity for protection against interference.

5. The resolving power of the guidance system precludes any possibility of solving the problem of attacking two or more bombers flying in a close formation.

6. A single guidance equipment complex can control only a single missile from the instant of launch to the final instant of the guidance procedure.

7. It is difficult to maintain the "Nike" missiles in storage for a prolonged period of time without disrupting their flight characteristics. They can be stored only at a definite temperature and under conditions of precise humidity.

8. The heavy boosters used by the "Nike" missiles, jettisoned in flight upon burnout, can damage structures, equipment and injure people, as they fall to earth. This makes it necessary to advance the launching points as far as possible from the objectives being defended.

9. The high cost of the missile (15-25 thousand dollars).

§2. THE SINGLE-STAGE ANTIAIRCRAFT "OERLIKON" MISSILE FOR GROUND UNITS

Another guided missile that is rather well covered in the literature is the single-stage antiaircraft guided "Oerlikon" missile developed by the Swiss firm of Oerlikon-Buehrle. The equipment used for the guidance system of the missile was developed by the Swiss firm of "Braun-Boveri," with participation by the firm "Contraves."

The first model of the "Oerlikon-250" missile was produced in 1950. The design of the missile has now undergone substantial changes. The latest modification of the missile has been designated "Oerlikon-56."

A liquid-fuel rocket engine [ZhRD] powers the missile for a period of 30 sec. Engine burnout occurs at an altitude of about 9 km.

The frame of the missile has a well streamlined shape. Four triangular-shaped main supporting surfaces have been mounted on the frame in a cruciform arrangement to provide the required lift. These surfaces shift along the longitudinal axis of the missile during flight to offset changes in the position of the centers of wing gravity and pressure. There are four small control surfaces in cruciform arrangement in the tail section of the missile.

Fig. 116. Target-track radar in guidance system for the "Oerlikon" missile.

Fig. 117. Guidance radar unit for the "Oerlikon-54" missile with two coaxial antennas for wide and narrow beams.

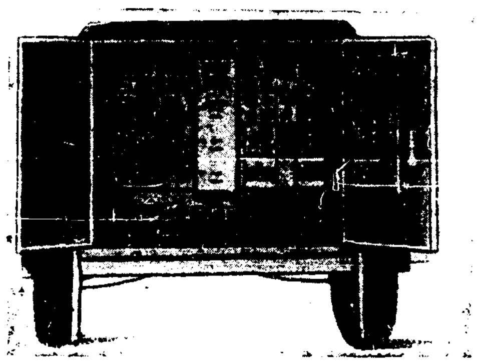

Fig. 118. Computer for the guidance system of the antiaircraft "Oerlikon" missile.

Missile control during flight is achieved during the active phase of the flight by deflecting the combustion chamber of the engine and by means of the control surfaces at the tail; missile control during flight along the passive segment is achieved exclusively by means of the control surfaces.

The missile is launched by means of a paired launching installation.

In actual practice, the launching angles may vary within a range from 10 to 90°.

The initial acceleration during missile launch is equal almost to 3 g.

The guidance system. The "Oerlikon" missile is guided to the target along a radar beam by means of the three-point method. Here the trajectory of missile flight will take the shape shown in Fig. 70.

The equipment complex of the guidance system of the "Oerlikon" missile includes:

1. The ground equipment consisting of a target-track radar (Fig. 116), a guidance radar unit (Fig. 117), and computers (Fig. 118); the guidance radar unit has two transmitters and two antennas which form two beams of various widths: one beam is narrow, to guide the missile to the target; the second beam is wide, to "capture" the missile during launching and insert it into the narrow guidance beam. The computer is necessary in order to control the radarbeam transmitter and to recalculate the coordinates of the target during the transmission of these coordinates from the target-track radar unit to the radarbeam transmitter; the distance between the target-track radar unit and the radarbeam transmitter is taken into consideration here (correction for parallax).

2. The on-board equipment of the missile, consisting of a re-

ceiver with antennas for the reception of radar signals (at first from the wide-beam transmitter and then from the narrow-beam transmitter) and the on-board control system convert the signals received by the missile into forces which act on the corresponding missile control surfaces for purposes of control.

The process of guiding the "Oerlikon" missile consists in the following. After detection of a target, the target-track radar, which is a conventional target-track radar unit, locks on and automatically tracks the target, yielding the instantaneous coordinates of the target through a computer to the guidance radar unit. The computer, in addition to taking into consideration the correction factors for parallax, automatically determines and sets the angle of missile elevation on the launching installation and determines the predicted lead with respect to the azimuth during missile launch.

Immediately after the launching, approximately during the first six seconds, the missile is controlled by means of a gyroscope and flies a virtually straight line with the angle of elevation set during the launch. Then the missile enters the wide beam of the guidance radar unit and, moving along this beam, is inserted into the narrow beam which is maintained continuously in a line with the target by means of the computer that utilizes the data provided by the target-track radar unit.

When a missile carrying a receiving device with four slot-type antennas directed to the rear enters the zone of radar beams (initially, the wide beam, and then the narrow beam), it begins to receive radar signals from the guidance transmitters and works out signals to control the control surfaces by means of the on-board control systems in such a manner as to cause the missile to fly along the axis of the beam directed toward the target throughout the entire guidance period.

On contact with the target or in the immediate vicinity of the target, the missile explodes.

Ground equipment, organization of guided-missile units, and fire-control (Fig. 119). The organization of ground guided-missile units is standard and is used by both the Swiss army and the Swiss air force.

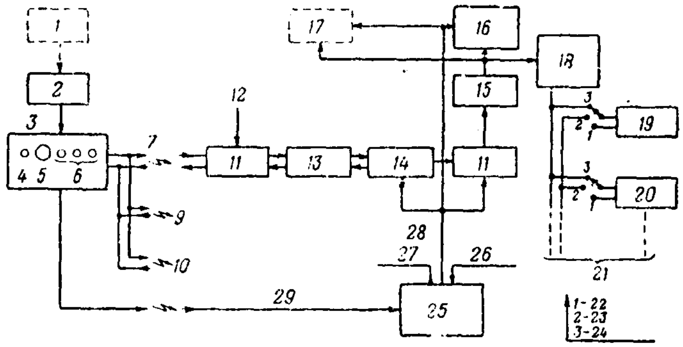

Fig. 119. Organization of units firing "Oerlikon" guided antiaircraft missiles and the fire-control set-up. 1) Long-range acquisition radar network; 2) acquisition radar unit of central command point; 3) central command point; 4) operator's acquisition-radar indicator; 5) commander's acquisition-radar indicator; 6) portable acquisition-radar indicators for three batteries; 7, 9, and 10) transmission lines for target coordinates to batteries Nos. 1, 2, and 3, respectively; 11) computer to account for parallax correction; 12) elevation search sector installation; 13) coordinate converter for elevation search in sector; 14) battery radar unit in combination with optical device for target tracking; 15) prediction computer for compensation of dynamic error; 16) guidance radar unit with angular-velocity and acceleration limiter; 17) reserve interference-resistant radar guidance unit; 18) prediction computer for launching phase; 19) launching site No. 1; 20) launching site No. 2; 21) additional launching site; 22) position of switch for suspension of missile from launching installation; 23) position for spinning gyroscope; 24) position for launching missile; 25) battery command point; 26) all input control signals; 27) all command signals transmitted over some distance; 28) target designation with respect to azimuth from battery command point; 29) target designation with respect to azimuth from central point, depending on direction of attack.

The unit consists of three batteries and a central command point. The unit's radar equipment consists of an acquisition radar set up at the command point and a target-track radar unit at each of the batteries; there is also a guidance radar unit that is made up of a two-beam transmitter. Moreover, each battery is equipped with a tracking telescope in order to be able to track the target both by means of the radar as well as with optical facilities when visibility is good.

The assumption is that timely warning of the approach of enemy aircraft (at distances up to 300 km) can be achieved by means of a long-range acquisition radar network. In the absence of such a network, this function is carried out by the radar unit of the command point, whose effective range may reach 100 to 120 km.

Fig. 120. Guidance radar equipment for the "Oerlikon-250" missile, with two separate antennas to form the wide and narrow beams.

Data on target position (azimuth and distance), determined by the acquisition radar unit of the central command point, are transmitted to the battery target-track radar unit of each battery. During this transmission these data are passed through a coordinate converter which searches a definite sector with respect to elevation λ, and the sector can be controlled manually. Upon receipt of these data, the battery radar unit begins to search the given sector with respect to elevation and as soon as the target is detected the data regarding the position of the target are immediately transmitted to the command point. The transmission of these data from the command point to the battery target-track radar unit and back is accomplished by means of a computer de-

vice which takes into account the parallax correction that must be introduced as a result of the distance that separates the radar unit of the central command point and the battery target-track radar units, a distance that may reach as high as 15 km.

The battery target-track radar unit, having determined the coordinates of the target, begins to control the guidance radar unit and the launching installation, setting these in the proper direction. For more exact setting of the beam on the target during the transmission of the target coordinates from the target-track radar unit to the guidance radar unit, account is taken of the parallax correction factor by means of the computer device and this correction factor must be introduced because of the distance separating the radar units; this distance may attain a maximum magnitude of 800 m. Moreover, in order to ensure higher accuracy of missile contact with target, another computer device introduces a certain prediction factor in the direction of the beam that is required to offset the shift (dynamic error) of the missile with respect to the central axis of the radar beam.

To eliminate errors during launching, the launching installation is also controlled by means of the computer devices which take into consideration the correction for parallax caused by the distance that separates the guidance radar unit and the launching installation; in addition, the computer devices determine the magnitude of the required azimuthal prediction at launch and introduce a correction to the basic angle of elevation for the angle of attack of the missile so as to take into account the motion of the beam during the first six seconds.

Prior to the launching of the missile the positions of the guidance radar unit and the launching site are collated with the target designation (with respect to azimuth), transmitted by the battery command point, and this information, in turn, is transmitted to

the battery command point from the central command point.

As has already been indicated, the guidance radar unit consists of two independent transmitters operating on closely similar frequencies and feeding two antennas to form a wide beam of 20° and a narrow beam of 3°. In the first modification of the missile (the "Oerlikon-250") the guidance radar unit for the forming of the wide and narrow beams was provided with two separated antennas (Fig. 120). In the last modification ("Oerlikon-54") both of the antennas were situated on a single axis and were set into motion by a common motor (see Fig. 117). The transmitters and their antennas are mounted on three-wheeled carriages. The transmitters with their modulators are positioned directly behind the antenna paraboloids. The auxiliary instruments are mounted in the bottom part of the installation. The antennas are made to turn so that the upper hemisphere can assume any position.

The on-board missile-control system can provide extremely significant overloads. However, if the proper safety measures are not taken as the missile is being guided along a radar beam against a rapidly maneuvering target, missile control may be lost. This can happen if the beam shifts so rapidly that the missile cannot follow it. In order to avoid this situation, a special circuit with a computer has been provided for the radar-beam transmitter of the "Oerlikon" system, and this circuit limits the maximum angular velocity and acceleration of the transmitter antennas.

All of the computer instruments and devices have been assembled in a single centralized computer installation that is mounted on a trailer on wheels.

<u>The on-board equipment</u>. The entire process of guiding the "Oerlikon" missile, depending on the operational features of the control system, can be divided into three phases: the launch, the flight

within the wide and narrow beams, and the flight after engine burnout.

Since the "Oerlikon" missile is launched from a launching installation requiring no long guide rails, and without boosters, its initial velocity is quite low. As a result, the effect of aerodynamic forces on the control surfaces is insignificant during the launch and the missile is controlled virtually exclusively by the deflection of the reaction stream (by inclining the combustion chamber).

Fig. 121. Tail section of the "Oerlikon" missile with four slot antennas positioned around the periphery.

During the first six seconds of flight, the mechanism which controls the rotation of the combustion chamber receives control signals from the gyroscope system. At the end of these six seconds, the aerodynamic forces increase substantially, the control surfaces become effective and begin to exercise control. At this instant of time the missile enters the wide beam and the second phase of the guidance procedure begins.

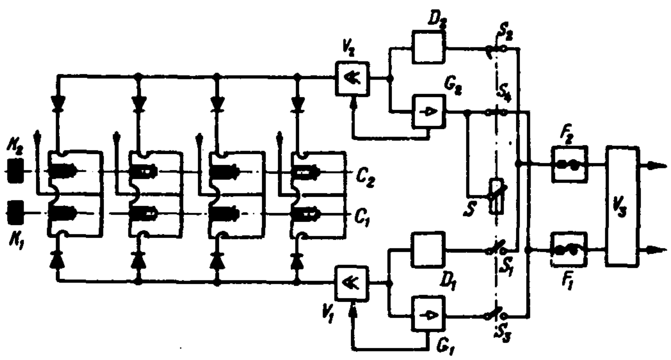

Fig. 122. Block diagram of receiving unit of the equipment on board the "Oerlikon" missile.

Control by means of gyroscopes, which is employed at the beginning of the flight, continues for a certain period of time in order to pro-

duce the damping moments with respect to the lateral axes of the missile. This control ceases as soon as there is no longer any danger of the missile turning over as a result of strong jolts (because of excessive control-surface deflection).

After the missile first enters the wide beam, and then the narrow beam, the receiving device aboard the missile begins to receive the radar signals from the ground transmitter by means of four slot antennas that are directed to the rear and are mounted in the tail part of the missile frame on special lugs (Fig. 121).

As is shown in Fig. 122, each reception antenna is connected to two frequency filters (resonators C_1 and C_2), respectively tuned to the frequency of the wide- and narrow-beam transmitters, and these filters separate the wide- and narrow-beam signals and direct them to two individual channels. If the missile is not in the equal-signal zone of either one of the two beams, the received signals are amplitude-modulated with the frequency of beam rotation.

The high-frequency oscillations of each channel are individually converted by the first detector at the output from the reception resonators into intermediate-frequency signals which are applied to the corresponding amplifiers (V_2, for the narrow beam, and V_1, for the wide beam). After amplification, the signals are rectified by the second detectors (G_1 and G_2) at the outputs of which low-frequency signals are obtained (error signals). The amplitude and phase of these signals characterizes the position of the missile in the beam. The reference signals (reference voltages) are produced in the demodulators D_1 and D_2; these voltages are transmitted to the missile in the guidance system of the "Oerlikon" missile by means of frequency modulation of the signals emanating from the transmitters, and this frequency modulation is synchronous with the frequency of beam rotation.

The error signals and the reference voltages have the same frequency, identical for both of the channels, and equal to the frequency of beam rotation. These signals are applied to the remaining portion of the missile control system through the filters F_1 and F_2, tuned to this same frequency.

An automatic switch (relay S) is installed at the input to the filter F_1 and F_2 to switch control from the wide beam to the narrow beam. The switching of the control is accomplished by the voltage of the wide-beam error signal at the instant at which the percentage modulation of the wide-beam signals drops below a certain given magnitude. To provide for smooth transition of control from the wide beam to the narrow beam during the switching operation, automatic gain control of the corresponding signals is employed in the receiving unit.

The subsequent portion of the on-board control-system circuit determines instantaneously the position of the missile in space with respect to the main axis of the transmitter beam in conic coordinates ε and φ (see Fig. 69) on the basis of the information contained in the error signal. Since the control of the "Oerlikon" missile is carried out in pitch and in heading, i.e., in rectangular coordinates (x, y), the conic coordinates are initially transformed into cylindrical coordinates which, for each specific instant of time, or polar coordinates (ρ, φ), and are then transformed into rectangular coordinates. This transformation is carried out by means of computer devices (coordinate converters) in accordance with a preset temporary missile flight program (Fig. 123).

To prevent the disruption of missile control as it rotates about its longitudinal axis (which cannot be prevented in the case of the "Oerlikon" missile), the control signals are recalculated from the fixed spatial coordinate system (x, y) to a system (x', y') that is

rigidly connected to the missile. This recalculation is carried out by means of the computer that is connected to the free gyroscope controlling the missile through the roll channel.

There is yet another gyroscope to damp the motion of the missile with respect to its lateral axes in the on-board control system of the "Oerlikon" missile. This gyroscope transmits additional components proportional to the angle δ between the axis of the beam and the longitudinal axis of the missile to both of the control signals; this angle arises during the guidance process and increases as the missile gains distance from the guidance transmitter.

The control signals worked out by the on-board missile-control system deflect the combustion chamber of the missile and the control surfaces through the appropriate pitch and heading angles by means of servodrives in an effort to maintain the missile on the axis of the beam.

During the launch and as the missile is flying at its greatest velocities (before engine burnout), at the time when the effectiveness of the control surfaces has increased and the required magnitude of the control-surface deflection for execution of maneuvers has diminished, the control of the efficiency and action of the control signals on the control units of the missile is achieved by changing the control factors (i.e., by changing the transfer ratios in the control apparatus).

At the end of the second missile-flight phase there is a noticeable shift in the center of missile gravity in connection with the consumption of fuel during the flight, which is a function of the flight time and independent of the flight altitude and velocity. Moreover, with a change in flight velocity and missile angle-of-attack with respect to time the center of pressure of the aerodynamic forces

shifts. Both of these factors affect the magnitude of the missile-stability arm (the distance between the center of gravity and the center of pressure), which in turn affects the magnitude of the lift force and the maneuverability of the missile. In connection with the fact that the magnitude of the stability arm depends in greater measure on time than it does on velocity, the control of the "Oerlikon" missile is programmed only with respect to the time function.

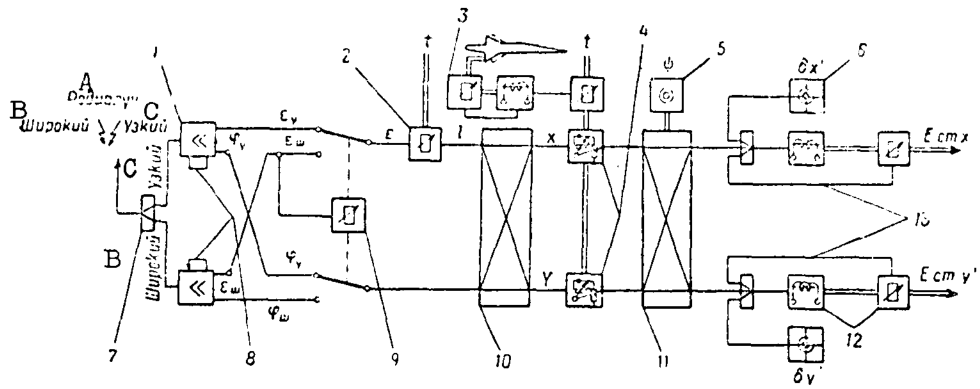

Fig. 123. Circuit of the control system for the "Oerlikon-54" missile. 1) Separation of amplitude and frequency modulation; 2) transformation of conical coordinates into cylindrical coordinates; 3) follow-up system for wing-shift; 4) computer and amplifier unit; 5) free gyroscope to control roll angle; 6) precession gyroscope to control pitch and yaw; 7) separation of wide- and narrow-beam signal frequencies; 8) gain control; 9) switch of control from wide beam to narrow beam; 10) conversion of polar coordinates into rectangular coordinates; 11) transformation of spatial coordinates into the coordinates connected to the missile; 12) electrohydraulic servodrive system; 13) position indicator; A) radar beam; B) wide; C) narrow.

Upon completion of engine operation (approximately at an altitude of 9 km) missile control is exercised exclusively by the control surfaces. Along the passive segment of the missile-flight trajectory the aerodynamic forces acting on the missile as a whole and on the control surfaces in particular diminish continuously as a result of the reduction in flight velocity and the drop in air density as the missile gains in altitude. At this instant of time the stability arm increases

because of the shift of the center of pressure and there is a significant increase in the stability coefficient of the missile; the controllability of the missile is reduced. In order to prevent this situation a time-programmed shift of the missile wings to the front is employed in the case of the "Oerlikon" missile to change the position of the center of pressure and, consequently, to reduce the stability arm and increase the controllability of the missile. Simultaneously the control coefficients are increased in order to offset the reduction in the efficiency of the control units as a result of the shutting down of the engine and the cessation of the action of one of the component forces — the force of gravity.

With this method of regulation, the change in the lateral acceleration of the missile with respect to the axis of the beam (the dynamic guidance error) is a weak function of time throughout almost the entire flight of the missile along the trajectory.

§3. THE "TERRIER," A TWOSTAGE ANTIAIRCRAFT MISSILE FOR NAVAL FORCES

The "Terrier" is a twostage antiaircraft guided missile intended for antiaircraft defense of naval vessels and coastal facilities.

The development of the "Terrier" missile was begun in 1945.

This missile is in series production since 1953. At the present this missile is part of the armament aboard cruisers and destroyers. The basic function of these modified vessels will be to provide for the antiaircraft defense of high-speed operational units, but they will also be able to execute combat operations against naval targets and coastal facilities.

The sustainer and booster engines are both of the solid-propellant type. The booster engine functions for a period of 3 to 4 seconds.

The "Terrier" missile has the following aerodynamic design. Ap-

proximately in the middle of the cylindrical frame (tapering to a point at the forward end) there are trapezoidal wings in cruciform arrangement which turn and serve simultaneously as the lifting and control surfaces of the missile. The tail surfaces are fixed in position and serve only for purposes of stabilization. They are shifted through an angle of 45° with respect to the wings in order to avoid the harmful influence of airflow interference. The receiving antennas are mounted on the tail stabilizers of the missile.

The warhead and radiofuse are mounted in the missile's nose. In the midsection of the missile, in the region of the wings, there are the servomechanisms that control the rotation of the wings, and a portion of the control-system equipment is also situated here. The sustainer engine is mounted between the wings and the tail control surfaces. The radar guidance equipment is mounted in the tail section of the missile, close to the antennas.

The booster engine has also been provided with four stabilization surfaces.

The missile is launched at sea from paired fully automated launching installations that are set at the required angle. Special ground mobile launching installations have been developed for purposes of adapting this missile for ground operations (the army and the marines).

The guidance system. The "Terrier" missile is guided to its target along a radar beam in accordance with the three-point method. The equipment complex of this missile-guidance system includes the following: naval (or ground) radar guidance stations developed for the various ships by a number of firms, and conventional on-board guidance equipment for the given guidance systems and methods.

Seagoing equipment for launching and guidance. The launching installation for the launching of the missiles has a cylindrical base

column and two guide rails. There are bunkers in the holds beneath the launching installations to house the combat-ready missiles. Between

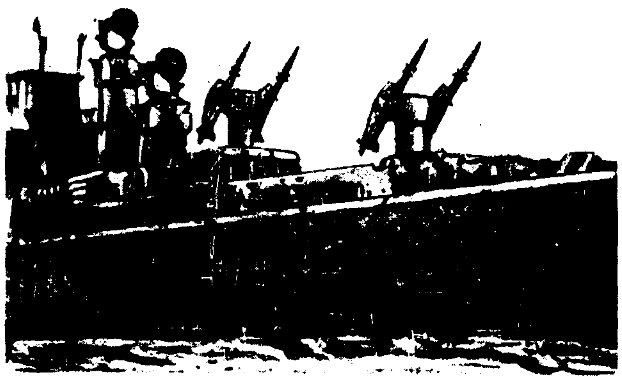

Fig. 124. Launching installation with "Terrier" missiles and guidance radar units aboard the cruiser "Boston."

these bunkers, close to the top deck, there is a specially outfitted enclosure from which the missiles are subjected to periodic inspection, testing, and repair. Beneath the top deck there is also an enclosure for the control mechanisms of the launching installations and the mechanisms which control the automatic transport of the missiles to the guide rails of the launching installations. The missiles and the pertinent equipment occupy all of the silos of the vessels from the keel to the top deck.

Two paired launching installations can fire 8 missiles per minute (two salvos of two missiles from each installation), and this rate is limited by the effective rate of the missile-transport machinery.

The radar equipment for the guidance of the "Terrier" missiles aboard the cruiser "Boston" consists of two target-track and guidance radar units of the AN/SPQ-5 type and a fire-control system of the AN/MSG-3 type, whose function it is to select the target and prepare the missile for launch.

The guidance radar units are mounted closer to the midsection of the vessel, above the launching installations (Fig. 124), and the antenna of one of the guidance radar units is mounted higher than that of the other. Each of the guidance radar units generally controls a separate launching installation, thus making it possible to guide the missiles simultaneously against two targets.

As soon as the guidance radar unit "locks on" to a target, the guide rails of the launching installation are set at a predetermined launching angle and are subsequently shifted in accordance with the signals provided by the radar unit. The launching of the missile is carried out on command of the fire-control officer. Each of the launching installations can fire either a salvo or a single missile. After the launching, the missile enters the beam of the radar guidance unit that operates to track the target and the missile moves along the axis of the beam, responding to all movements of the latter. Each guidance radar unit can guide one or several missiles simultaneously against a single target or a group of aerial targets. Both of the radar units can track simultaneously a single common or two individual targets. In firing at single targets flying at great distances, the speed of firing may be restricted by the potentials of the vessel's radar equipment.

"Terrier" missiles launched from the cruiser "Boston" were able to destroy jet-propelled target drones flying at altitudes up to 15 km, at velocities of the order of 900 km/hr.

The modification and arming of the second cruiser (of similar design) – the "Canberra" – with "Terrier" missiles was completed in May of 1956 (Fig. 125). The launching installations aboard this destroyer are identical with those aboard the cruiser "Boston," but the guidance radar units aboard the cruiser "Canberra" differ substan-

tially from the radar equipment aboard the Boston ; the former radar units are used not only for purposes of guidance but serve also as

Fig. 125. Launching installation and guidance radar equipment aboard the cruiser "Canberra "

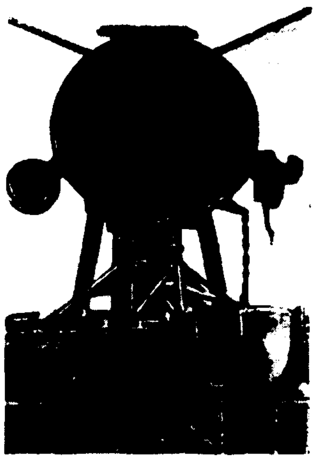

Fig. 126. Guidance radar unit for anti-aircraft "Terrier" guidance missiles aboard the destroyer "Hyatt."

long-range acquisition radar units.

The first destroyer equipped with guided "Terrier" missiles of the United States Navy, the "Hyatt," was to become operational in 1957. This ship is equipped with a guidance radar unit that for the first time combines the functions of missile guidance and fire control (Fig. 126). This radar unit, developed by the Reeves Instrument Company, is a modification of the earlier versions intended for cruisers, and differs from these earlier versions in its greater compactness, effective range, and greater guidance accuracy. It also includes automatic monitoring equipment.

As soon as an aircraft is detected on the screen of the station's indicator, signals are generated and transmitted to the detected ob-

ject in order to determine and recognize the origin of the aircraft. If it is established that the aircraft is "unfriendly," the radar unit begins to track the aircraft, transmitting the required data through a computer device to the missile launching installation. As a result of the coordinated operation of the radar unit and the data transmission system, the launching installation is moved into proper position, the missile is launched and inserted into the radar beam, and is finally guided along the beam to the point of target interception.

All existing versions of systems to guide the "Terrier" missile along a radar beam are incapable of achieving target interception in the case of targets flying at low altitudes. In this connection, the Convair Company is working on the development of a version of the "Terrier" missile which will be equipped with a special homing head designed for operations against low-flying targets.

It is also well known that other types of guided missiles that are modifications of the "Terrier" missile are being developed for the United States Navy; these missiles are intended for inclusion as part of the armament of surface vessels. The largest of these is the "Talos" (effective range, 160 km), which is to become part of the weaponry of 8 cruisers. There are also reports to the effect that the guidance system for the "Talos" missile represents an improvement over the guidance system of the "Terrier" missile. A number of sources have indicated that the "Talos" is equipped with a homing head. Another missile is the "Tartar" (effective range, 32 km), which is a smaller version of the "Terrier" missile, but superior to it in terms of characteristics and because of the fact that it has been equipped with a homing head.

§4. GUIDED BALLISTIC MISSILES "CORPORAL," "REDSTONE," AND "THOR"

Depending on combat designation, ballistic missiles exhibit vari-

ous effective ranges. The United States Army and the armies of a number of NATO countries have been equipped with such missiles.

"Corporal." Singlestage ballistic missiles of the "Corporal" type, intended for destruction of ground targets, are employed to reinforce the fire power of artillery and to offer direct support to ground forces.

The missile is equipped with a liquid-fuel rocket engine (ZhRD) that is capable of developing thrust of 9070 kg. Air compressed to a pressure of 170 kg/cm^2 is employed to feed the propellant into the combustion chamber.

The control units consist of four aerodynamic control surfaces and gas vanes mounted on the stabilizers. The gas (jet) vanes and the nose section of the missile are made of plastic.

The "fire" complex of the "Corporal" missile consists of the missile itself, the control equipment, the monitoring-testing equipment, and the equipment for servicing and transporting the missile.

The control system for the "Corporal" missile is a combination of an inertial (gyroscopic) and command guidance system, of which the former functions during the initial phase of the missile flight, while the latter is used to correct the trajectory of the missile both prior to and after engine burnout. Such a system is referred to as a control system with radial trajectory correction.

The control equipment produced by the Dzhilfillan [sic] Company requires three trailer trucks for transportation. It includes the following: an AN/MPQ-25 radar unit for purposes of tracking and transmission of commands, an AN/MPQ-7 radar unit which operates on the Doppler principle to measure missile velocity, and an AN/MRQ-7 computer which uses data from the tracking radar unit and from the Doppler radar unit to calculate and work out the required commands. The Doppler radar

system, besides measuring the velocity of the missile, determines the instant of engine burnout and fuse activation, sending the corresponding commands to the missile.

In addition, an optical tracking system is employed to facilitate missile tracking during launching in clear weather.

The on-board equipment of the missile consists of an antenna situated on one of the stabilizers, an on-board receiver, an autopilot, and an on-board responder that functions in conjunction with the Doppler system which measures missile velocity.

The missile is launched and controlled in the following manner.

After selection of the firing position and the checking out of the missile and its equipment at the control point, the initial data for missile-flight programming are determined and set for a given range. These data completely determine the point in space at which the engine is to burn out, and in addition these data determine the position and velocity of the missile at that instant of time. The parameters of missile motion at that point determine the ballistic trajectory along which the missile is to fly to the target after engine burnout.

After the flight program has been fed into the programming mechanism of the missile, the missile is launched. The launch is carried out vertically, and after several seconds the missile is turned in the direction toward the target and inserted into the beam of the radar guidance unit. From that instant the command guidance system takes over to correct the trajectory of the missile, and the accuracy of this command guidance system is higher than that attainable with programmed guidance.

The control system of a ballistic missile must carry out two tasks:

1) control missile position or, in other words, ensure proper spatial orientation (attitude) of the missile as it passes the calculated critical point at which engine burnout takes place;

2) control missile trajectory with respect to the azimuth or, in other words, maintain the missile in its proper heading.

These tasks are carried out by the guidance system (for the "Corporal" missile, these tasks are carried out by the command system).

After the missile has been inserted into the radar beam, it must fly along the equal-signal zone of this beam. Deviation from the equal-signal zone is determined by the guidance radar unit which, by means of a computer device, works out the appropriate azimuthal commands and transmits these to the missile in order to maintain the missile on a heading directed at the azimuth of the target, in accordance with the program. Simultaneously the position of the missile on the trajectory is determined, since this affects flight range; in the case of an error, the commands to correct the position of the missile with respect to pitch are worked out and transmitted in the same way.

The correction of missile position with respect to azimuth and pitch is a step that is taken both during the active phase of the trajectory of a missile (prior to engine burnout), as well as during the passive phase. The correction commands are received by the on-board receiver and transmitted to the autopilot which controls the missile by means of the gas vanes during the active phase of the trajectory, which lasts about one minute, and by means of the aerodynamic control surfaces during the passive phase. The trajectory is corrected during the passive phase of the flight because despite all efforts and the comparatively high accuracy of the preliminary calculations and the functioning of the control system, the missile will not pass exactly through the calculated critical point, but somewhere in its vicinity,

because of the nonsteady operating regime of the engine, and the effects of wind and other factors.

The same can be said about missile velocity as the missile passes through the critical point. Although liquid rocket engines, in comparison to solid rocket engines, exhibit the advantage that the cessation of engine operation may be brought about more precisely, the shutting down of an engine, regardless of type, however, virtually never takes place at the desired point on the trajectory. Because of the untimely extinction of the engine, missile velocity at the critical point may differ from the calculated velocity. The difference between the actual velocity and the calculated velocity, determined by the radar unit operating on the Doppler principle, is fed into the computer device which works out the corresponding commands and subsequently corrects the flight of the missile with respect to range. All of the correction commands transmitted to the missile during this phase of passive flight, in which the missile finds itself in the rarefied layers of the atmosphere (at the apex of its trajectory), are transmitted to a memory (storage) device which accumulates all of these corrections until the missile returns to the denser layers of the atmosphere, and this is done so as to enable the missile to execute these commands. Thus the last trajectory correction for the guided ballistic "Corporal" missile is introduced on the descent branch of the missile's trajectory.

The possibility of correcting the trajectory of the "Corporal" missile is a tremendous advantage of this system, particularly so in view of the fact that radial corrections are extremely accurate. A shortcoming of the radiometric method of correction is the fact that this method is subject to enemy radio interference and the fact that it is difficult to employ this method for intercontinental rockets,

because intensive ionization occurs around intercontinental rockets moving at great speed, and this ionization prevents the passage of radio commands.

Units equipped with "Corporal" missiles have been organized by the United States Army. These units, as a rule, are independent operational units and include such support units as infantry and armored battalions for defense, reconnaissance aviation, engineer units, and communications and support units.

The very smallest of the combat units which can execute independent operations, collect information, and control fire is the company which includes 249 officers and enlisted men. The company consists of two batteries, a headquarters unit, a headquarters battery, and combat battery platoons.

The "Redstone." The singlestage "Redstone" missile is intended to destroy ground targets well behind an enemy's rear lines. The missile consists of two parts: a tail section, and a nose section which is jettisoned in flight.

The missile is powered by a liquid rocket engine producing 34,000 kg of thrust, developed by the "North American Company." The fuel-feed system is of the turbopump variety.

The powerplant, fuel tanks, air control surfaces, and the basic control surfaces are situated in the tail section of the missile. The warhead, control system, and three small control surfaces for missile control in the case of velocities corresponding to a flight Mach number of $M = 5$ are carried in the forward section of the missile.

The "firing" [combat] complex of the "Redstone" missile consists of the missile, the monitoring-testing equipment, the transportation facilities, and the fuel trucks. The mobile launching installation can be set up virtually in any terrain.

The control system for the missile is of the inertial kind. It represents the latest modification of the autonomous control system for the German A-4 rocket, but differs from this system in that it can be used not only during the active phase, but for the correction and stabilization of the flight of the nose section after the separation of this section from the main rocket.

The control system is produced by the "Sperry-Rand Company" (a division of the "Ford Instrument Company"). The inertial system includes two accelerometers which measure acceleration in two planes (vertical and horizontal), a gyrostabilized platform for mounting of the accelerometers and the computer.

Unlike the "Corporal" missile, the control system for the "Redstone" missile has no ground control equipment.

The launching of and the control of the missile are handled in the following manner.

After the selection of the firing position an exact measurement of the coordinates of the launching site is carried out. As soon as the coordinates of the launching site and the target are known, the ballistic flight trajectory of the missile is calculated and programmed for a given range, with the various factors affecting missile flight being taken into consideration here. During this time the missile is assembled and checked and the instruments of the inertial control system are adjusted. Once the missile is mounted in its vertical position and fueled, the program of the calculated trajectory is fed into the control system.

Upon completion of all of the preparatory work the missile is launched. For a period of several seconds the missile rises vertically and it then turns in the direction to the target.

The inertial control system determines the calculated point at

which the engine is to burn out and issues the command for the cessation of fuel feed to the engine. The missile continues its subsequent flight along a ballistic trajectory.

Because of thrust nonuniformity, crosswind, or other forces acting on a missile, the missile is subjected to accelerations which are picked up by the accelerometers. The system makes it possible to determine the magnitude of the deviations from the required trajectory, and the computer calculates the corrections which must be introduced to return the missile to the proper trajectory. The final corrections are introduced into the trajectory of the missile when it returns from rarefied outer space to the dense layers of the atmosphere.

The inertial system of the "Redstone" missile, in comparison with the radio-trajectory-correction feature of the control system in the "Corporal" missile, exhibits one significant advantage, i.e., absolute freedom from interference with the guidance system because of the absence of any ground control equipment and any link between the missile and the target, which also serves as an important advantage of this system.

A shortcoming of the system is the possibility of introducing a variety of errors; geodesic (because of inadequately accurate topographic coordination), errors resulting from imperfections in the gyroscopes and accelerometers, etc.

"The Thor." The "Thor" missile is a singlestage ballistic missile of medium range intended for the destruction of important ground objectives deep behind an enemy's rear lines.

This missile is powered by a liquid-rocket engine developing 68 tons of thrust.

The inertial control system is well known by the designation "Echiver" [sic].

The basic elements of this system include the gyrostabilized platform on which three integrating gyroscopes are mounted and oriented with respect to the three axes of the missile, i.e., pitch, yaw, and roll; these gyroscopes serve as accelerometers. In addition, there are computers and other devices.

All in all the system employs six gyroscopes; three for purposes of stabilization of the platform, and three as the sensing elements of the system. All the gyroscopes of this system are floating, integrating high-accuracy gyroscopes of the HIG-4 type, developed by the Massachusetts Institute of Technology. These gyroscopes exhibit the following characteristics: the threshold of sensitivity is $8 \cdot 10^{-7}$ deg/sec; the kinetic moment is 10^4 g-cm·sec; the number of rotor revolutions is 12,000 rpm; the frequency of the supply voltage is stabilized with an accuracy to 0.001%; and the engine is air-cooled during flight.

The integrating gyroscopes used as the sensing elements provide the initial signals that are proportional to the velocity of the missile along each of the three main axes of the missile, and these are then integrated by the computer device and used to calculate the deflection of the missile with respect to each of the three axes. Thus the deflections of the missile from the calculated trajectory can be calculated for the planes of pitch and heading, and the distance covered by the missile from the launching site can be calculated. The computer calculates the correction factors and works out the commands that are transmitted to the autopilot for purposes of correcting missile trajectory whose program is fed into the storage device of the computer. In addition, the computer determines the instant of engine burnout, at which point the missile reaches the given critical point and attains the calculated velocity.

An inertial system of the kind used for purposes of guiding bal-

listic medium-range missiles functions for a relatively short period of time (about 4 minutes), as a result of which the drift of the gyroscope axes will be substantially less than in the case of inertial systems intended for piloted aircraft or airplane-type missiles with comparatively long flight times. As a result, the gyroscopes of the inertial "Echiver" [sic] system are used without any correction (for example, by means of the Schuler (earth) pendulum generally used in inertial systems intended for prolonged operation).

It has been reported in the press that the weight of the given inertial system is about 225 to 450 kg.

In accordance with a report issued by representatives of the "General Motors Company," an inertial system of this type may be adapted for the control of intercontinental ballistic missiles of the "Atlas" type, exhibiting a flight range in excess of 8000 km.

[Footnotes]

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261	Some sources maintain that the Hawk missile is guided by a radar beam (the beam-rider method) to the lead point calculated by ground computer equipment. Most authors consider the guidance system of the Nike to be of the command type.
262	There are reports in the press concerning the presence of a homing device in the Nike missile. Many sources do not mention this, and it is pointed out that the warhead is mounted in the nose of the missile. It is possible that these reports refer to more recent modifications of the missile.
263	Some sources report the effectiveness of the Nike missile to be 80%; however, this figure possibly refers to more recent modifications of the missile.

Chapter 11

FUTURE PROSPECTS FOR THE DEVELOPMENT OF CONTROL SYSTEMS

The development of guided combat missiles is proceeding along four basic trends:

1) the development of new subclasses of guided missiles;

2) the development of new operational-tactical (target) designations within existing classes and subclasses;

3) the development of new versions of missiles having the same tactical designations;

4) further improvements of existing guided missiles.

As part of the first trend we can, for example, include the work being done on the development of such subclasses as the "submarine-to-surface vessel" and "submarine-to-ground" missile, i.e., the "Polaris"; the second trend includes the development of the "Hawk" antiaircraft missile intended for the destruction of lowflying targets, thus supplementing the existing antiaircraft missiles that are incapable of destroying such targets, i.e., the "Nike" missile; the third trend includes the development of "Talos" and "Tartar" antiaircraft missiles to supplement the operational "Terrier" antiaircraft missile; the fourth trend includes the development of the "Nike-Hercules" antiaircraft missile, on the basis of the "Nike-Ajax," and the "Oerlikon-56" antiaircraft missile on the basis of the "Oerlikon-250" missile.

From the "ground-to-ground" class the most promising are the ballistic missiles designed for various effective ranges, and we have particular reference here to missiles capable of operating between

continents, i.e., intercontinental missiles.

There have been indications in the foreign press that in addition to missiles intended for the direct destruction of enemy military objectives, guided missiles of special designations may be developed, and we have particular reference here to the following:

a) missiles to produce active and passive interference with an enemy in a given region;

b) reconnaissance missiles to detect targets deep behind an enemy's rear lines. In the first case, equipment is mounted on the missiles to create active radar or similar interference, or provision is made to eject means for the creation of passive interference at the required point. The plans call for the installation of television equipment in the reconnaissance missiles.

The development of each new missile necessarily calls for the development of new or modernized control systems. Since a control system is developed in accordance with the aerodynamic and tactical-technical characteristics of the missile, there are as many versions of guided missiles as there are versions of control systems. This means that for two missiles that differ in terms of their characteristics completely identical control systems are virtually never employed. If, however, the same systems are employed, they will differ in terms of certain of the parameters of their individual links.

It was pointed out earlier that each control system must satisfy many tactical-technical requirements, of which the most important are the following: high accuracy, reliability, resistance to interference, adequate range, the possibility of utilization at any time of day and in any weather, minimum weight, and minimum dimensions for the onboard equipment. However, each of the known systems exhibits its unique shortcomings and does not satisfy all of the requirements. As a re-

sult, scientific-research work is constantly being undertaken both to improve known control systems and to seek out new methods of designing more perfect systems. The foreign press has taken note of the fact that in order to elevate the guidance accuracy of guided missiles by means of developed and operational systems, it is possible to proceed in one of the following three ways:

1) improve the on-board control system and its individual elements;

2) improve the individual links of the entire control system (the entire control loop);

3) the utilization of combined systems in which homing systems are used for guidance during the terminal phase (radar or infrared homing systems).

The on-board control system may be improved by using improved elements and component parts, and by positioning them in optimum fashion and fastening them reliably to the missile, i.e., by eliminating all factors which serve to impair missile stability. Missile stability may be improved also be selecting the best missile shapes, since the aerodynamic characteristics of the missile play an exceedingly important role in the design of the control system.

Let us trace the trends in the improvement of control systems through the pages of the foreign press.

The American experimental NAKA [sic] station is doing much work on simplifying control systems. An attempt is being made, for example, to create an on-board control system with a constant control moment in which the deflection of the control units will be changed automatically, depending on the flight velocity and altitude.

French research organizations are working on increasing the maneuverability of the missile substantially. It is known that the prob-

ability of destroying a target depends in great measure on the magnitude of the permissible accelerations to which a guided missile may be subjected. Proceeding from this point, French specialists proposed the design of the "Ruatle" [sic] missile, executed in the form of a coleopter (with annular wings), which should be capable of flight with great acceleration. The missile is designed to fly at low altitudes while subject to forces of 20 g's. This becomes possible because the missile is so designed as to have the basic parts of the missile carry out many functions simultaneously, and the design also provides for minimum missile weight, which given the relatively great surface of the annular wing, produces an insignificant specific load on the wing. The substantial acceleration forces that can be withstood by such a missile provide for high flight-trajectory curvature, which enhances the elevation of guidance accuracy and increases the probability of target destruction.

Much work is being done on improving the ground guidance stations from the standpoint of increasing guidance range, increasing their resistance to interference, and elevating guidance accuracy.

According to reports in the American press, the Raytheon Company has developed a new centimeter-wave oscillator tube, the platinotron, which makes it possible to achieve a radar-unit output power greater by a factor of 8 to 14 than with the utilization of contemporary magnetrons of the same dimensions. A tube of this type can increase the effective range of the acquisition and target-track radar units, as well as of the missile-guidance radar units, by a factor of almost two. The tube can operate in an amplification regime and in this case it is referred to as an amplitron. The amplitron is a wideband tube. In terms of dimensions it is smaller by a factor of four than conventional amplifier tubes exhibiting the same gain and it requires a

voltage lower by a factor of two. The new tube, in view of its comparatively small dimensions, may be employed in the on-board radar equipment of the missile. As a result, the effective range of the active radar homing systems can be increased.

In the case of ground equipment, the task at hand is to increase guidance accuracy, for which purpose new methods are being sought to increase the accuracy with which the instantaneous coordinates and other parameters of target and missile motion are determined, and highly accurate computer installations are being developed.

In addition to improving the radio-engineering devices, target- and missile-observation facilities are being duplicated in order to increase the ability of the guidance system to resist interference, i.e., optical facilities are being installed in parallel with the radar stations for use in the case of radar interference by an enemy.

To increase guidance accuracy during the terminal phase, combinations of various guidance and homing systems are being employed on an ever-increasing scale. The Americans show a pronounced tendency to use homing facilities not only in the newly designed missiles, but in improved versions of earlier missiles, i.e., the "Nike-Hercules" missile.

The great achievements attained in the area of infrared technology, and primarily such advantages of the infrared systems as high accuracy and resolving power, have now made it possible to replace the radar homing systems, in certain cases, with infrared systems. Thus, for example, a new version of the "Falcon" guided missile with a heat-seeking homing head is being developed in the USA, whereas an earlier version of this missile is equipped with a radar homing system.

The idea is now being expressed that it might be possible and even feasible to develop so-called mixed homing systems which combine radar

and heat-seeking systems. It is not difficult to achieve such systems, since both types of systems have much in common. An important advantage of such mixed systems would be their high resistance to interference. As an example, it would be possible to develop such a system for missiles of the "air-to-air" class, and this system would consist of a passive infrared homing system and a passive radar homing system. If a radar-interference transmitter were to be turned on aboard an enemy bomber for purposes of protection against guided missiles, the radar system could be employed to guide the missile to the source of the interference. If the aircraft is not equipped with interference equipment, the missile could be guided to the operating engines of the aircraft by the infrared system.

Since contemporary infrared systems make it possible to detect the radiation of certain stars during the day, it has been proposed hypothetically to employ such systems in astronavigational guidance systems.

There have been repeated references in the American press to the idea of utilizing homing systems for the terminal phase of the trajectories of long-range and intercontinental guided missiles. Such systems would be capable of increasing substantially the accuracy of guidance to targets situated well behind an enemy's rear lines. The proposals call for the utilization of an active radar system which can deliver a high-quality radar image of the terrain as the system which could, in principle, be utilized for the aforementioned purpose. This image of the terrain could be compared against a radar image of the selected region, said image prepared in advance and included in the missile as part of the program prior to missile launch. In order to carry out a guidance procedure of this type the missile must be equipped with apparatus capable of recognizing terrain automatically

by comparing the programmed radar image of this locality (terrain) with the image obtained by the system. This method has the significant shortcoming of requiring preliminary radar mapping of the enemy's terrain, i.e., preliminary reconnaissance of the opponent's territory is necessary. However, it was felt that if radar maps of each square mile of the earth's surface were prepared, exact guidance would become a matter of practical possibility for many points on any of the continents.

The mapping problem is current even today. But since the method of active "radiolocation" exhibits shortcomings (the possibility of interference produced by an opponent, cumbersome equipment, etc.), work is being done on seeking out other methods that would be more convenient and reliable. For this purpose the passive heat-seeking systems using the infrared radiation of all heated bodies and their temperature contrast have come into use. Such systems are capable of yielding high-quality "heat photographs" of a terrain, which can be used successfully for target recognition. Moreover, these systems can provide a detailed visual image of a terrain on the screen of an electron-beam tube.

Experimental research is presently being carried on in the USA to determine the possibility of utilizing passive radar systems for purposes of reconnaissance and mapping of terrain; these radar systems operate within the range of the very shortest of the centimeter waves (0.8 cm, 1.25 cm, 1.8 cm, and 3 cm). These systems, much like the passive heat-seeking systems, have been designed to detect signals that are emitted by all objects whose temperature is above absolute zero. It has been established that the capacity of the passive radar system to distinguish objectives on a terrain depends on the following factors: the apparent difference in temperatures between objectives,

the width of the antenna directivity pattern, the slope of the pattern with respect to the objectives, the polarization of the antenna, and the sensitivity of the receiving installation. The advantage of this system lies in its capacity to distinguish objectives with identical apparent temperature, because of the various polarization properties of the various objectives. Moreover, the passive radar system, in this frequency range, provides for great effective range in comparison with the infrared system, because of fuel losses to the atmosphere.

It has been demonstrated experimentally that the utilization of passive "radiolocation" makes possible the development of automatic objective [target]-tracking systems.

Particular attention is being devoted in the USA to inertial and astronavigational long-range guidance systems developed for intercontinental missiles. Both systems have many elements in common, and these are subjected to a constant process of improvement. At the present time, great achievements have been attained in the development of exact gyroscopes and accelerometers. Simultaneous work is being done along the lines of miniaturizing all of the on-board equipment of the missile control systems. According to statements made by American specialists, the inertial system is held to be the most promising in the USA for purposes of controlling intercontinental airplane-type missiles and ballistic rockets.

The development of a guided missile of any class and its guidance to various targets with high accuracy is a rather difficult assignment. But an even more difficult assignment is defense against guided missiles, particularly the interception of intercontinental ballistic missiles; the plans call for the surmounting of this problem by means of special guided missiles that have been designated antimissile-missiles.

On the basis of some preliminary data that appeared in the American press, the antimissile-missile must be a guided missile of the "ground-to-air" class, equipped with a nuclear warhead. It is the opinion of other specialists that the warhead of an antimissile-missile could be of a different type. The complexity of this problem is significantly increased because of the difficulties encountered in timely detection of ballistic missiles approaching a target at high speed. The warheads of such missiles are generally small in size, as a result of which their effective reflecting surface (for radiowaves) is extremely small, and this makes it impossible to detect a flying missile at great distances in sufficient time, even with high-power radar equipment.

The problem is even further complicated by the high speed and, consequently, the limited missile flight time in approach to target for fast launching of a counterattack. The approaching missile must be detected at a substantially greater range than is possible with the visible horizon of any of the acquisition radar units. As a result, their arises the problem of setting up acquisition radar stations well forward, in the direction from which an attack is anticipated. Moreover, the detection and subsequent tracking of a missile at great range naturally introduces serious errors into the determination of the missile's coordinates, and these errors are introduced into the computer devices that work out the data for the guidance of the antimissile-missiles. This will have an effect on guidance accuracy, which may be low, whereas for reliable destruction of the approaching missile it must be high.

We can see from the above that the guidance system of an antimissile-missile, consisting of a target-track and guidance unit, as well as of a computer, must exhibit great effective range and uniquely high

accuracy for the operations of all of its elements. This means that the system will be extremely complex and difficult from the standpoint of practical realization.

The opinion has been expressed that a defense system against intercontinental ballistic missiles may involve the utilization of infrared homing systems during the terminal guidance phase, since during flight in the dense layers of the atmosphere the intensely heated warhead of the missile will serve as a powerful source of infrared radiation.

The achievements in the development of rocket engineering have resulted in the design and launching of artificial satellites of the earth and space rockets. The first successful space flights were carried out by the Soviet Union and this is a triumph of Soviet science and engineering and a matter of great pride for the Soviet people.

The control systems used for the launching of the artificial satellites are complex and must exhibit great accuracy.

Many specialists in the Capitalist countries hold that the artificial satellites will doubtlessly have military significance, particularly satellites that are manned. Such satellites could be used for purposes of reconnaissance and the dropping of nuclear bombs. Special rockets are required for purposes of communications with such satellites. However, manned satellites can be launched after all of the necessary scientific data have been obtained by means of unmanned satellites. Methods are being worked out to prepare defenses against artificial military satellites.

The countries of the Socialist camp understand well that the conquest of outer space is directed primarily to the well-being of all mankind and will be most effective only in the case of peaceful coexistence of all governments, extensive international scientific coop-

eration, and the exclusion of any type of war as a means of attaining political ends by force of arms.

Future development in rocket engineering must lead to interplanetary flights, and the successful and precise launchings of space rockets to the moon and lunar space by the Soviet Union have laid the foundation for this effort.

Even more complex and more exact control systems are necessary for the control of interplanetary vehicles. The problem of space navigation is a special task of a specific branch of science and engineering and all of the questions associated with this problem must be considered in a separate examination.

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